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Human Respiratory Responses During High Performance Flight

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AGARD regrets the occurrence of a significant error in this publication.

Due to a change in page numbering sequence, the introductory pages have been numbered separately and hence page references throughout the text of the AGARDograph are not correct. All cross-references, as they appear, are two pages too high (eg a cross-reference to page 36 actually refers to page 34).

In addition, the pagination of the Appendices is incorrect. All page references to Appendices will be made correct by renumbering pages 67 to 83 as pages A-1 to A-17.

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARDograph No.312

HUMAN RESPIRATORY RESPONSES DURING HIGH PERFORMANCE FLIGHT

by

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This AGARDograph was prepared at the request of the Aerospace Medical Panel of AGARD.

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PREFACE

This study stemmed from the clear need to establish the basic respiratory responses, such as respiratory frequency, minute ventilation and peak flows of pilots during high performance flight; and preferably with as little encumbrance from added external resistance as possible. Such information allows an assessment to be made of the effectiveness of systems in current use in fulfilling these basic requirements, and gives direction to the design specifications of new systems. Measurement of other respiratory variables, such as end-tidal PCO_2, also allows the energy expenditure of pilots during flight to be derived; and this, in turn, has important implications for the design and performance of aircraft and personal conditioning systems. Finally, there is a need to establish the incidence, if any, of hyperventilation in flight, and the continuous recording of end-tidal PCO_2 provides the ideal means of achieving this.

Respiratory Symbology & Explanation of Units

In this study, the following standard symbols for respiratory physiology have been used throughout:

	Symbol	Definition
Quantitative Variables	P	Gas pressure in general
	V	Gas volume in general
	$\dot{V}$	Gas volume per unit time (flow)
	$\tilde{V}$	Instantaneous gas flow per unit time
	F	Fractional concentration of gas
	f	Respiratory Frequency
	R	Respiratory Exchange Ratio
	SA	Surface Area
	t	Temperature (amb - ambiant)
	$\dot{Q}$	Blood volume per unit time (flow)
Qualifying Terms : Gas (subcripts)	B	Barometric
	A	Alveolar
	I	Inspired
	E	Expired
	$\bar{E}$	Mixed expired*
	T	Tidal
	ET	End-tidal
	D	Dead space (s-subject; m-mask)
: Blood	a	Arterial
: General	ATPD	Ambient temperature and pressure,dry
	ATPS	Ambient temperature and pressure, saturated with water
	BTPS	Body temperature (37°C) and ambient pressure, saturated with water
	STPD	Standard temperature (0°C) and pressure (760 mmHg), dry
	NTP	Normal temperature (15°C) and pressure (760 mmHg).
	SWVP	Saturated Water Vapour Pressure

* a dash (-) above any symbol denotes a mean value.

Traditionally, aviation physiologists have expressed measurements of pressure in a variety of units, such as millimetres mercury, torr, pounds per square inch, and millimetres, centimetres and inches water. In this study, when quoting litereture, the units as originally published have been repeated but with conversion to the SI unit of kilopascals (kPa) enclosed in parentheses. The traditional units of millimetres mercury and centimetres water were employed in the study itself but again the SI conversion is included.

Height is the term used to denote the distance of an aircraft above ground level (AGL). Altitude is the term used to denote the distance of an aircraft above (or below) mean sea level (AMSL) and, in the world of aerospace, is mandatorily expressed either in feet or as a flight level (FL); for example, an altitude of 35,000 feet may also be stated as FL350. This study obeys that convention, but the SI conversion to metres is also given.

Finally, where necessary, values for numerical conversions from one unit to another have been taken from the revised standardization of units and symbols published in 1984 in Aviation, Space and Environmental Medicine.[1]

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HUMAN RESPIRATORY RESPONSES DURING HIGH PERFORMANCE FLIGHT (c)

by

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Summary

The respiratory responses of experienced military pilots have been studied during flight in a high performance jet aircraft.

The importance and relevance of information about these responses have been reviewed, with particular emphasis on the difficulties of in-flight recording and the history of such experimentation in four specific areas of respiratory physiology: respiratory frequency and flow, added external resistance, hyperventilation and the metabolic cost of flying.

In the present study, respiratory variables were measured continuously using an airborne system which recorded the output from physiological and aircraft instrumentation. In order to approach normal respiratory behaviour more closely, a specially designed low resistance breathing system was developed and used in conjunction with a modified infra-red carbon dioxide analyser. A unique feature of the latter, also specially developed, was the ability to calibrate the device during flight. Inspiratory flows (and hence volumes) and expired carbon dioxide tensions were recorded along with inspired gas temperature, cabin altitude and aircraft acceleration. Mask cavity pressure was recorded on several occasions in place of carbon dioxide measurement. Eighteen pilots completed a total of 46 experimental flights, 23 of which involved carbon dioxide analysis. Three set flight profiles (two general handling and one simulated combat) were precisely defined to allow comparability between subjects. A fourth, less structured but high workload sortie, involving air combat manoeuvring (ACM), was flown on two occasions.

Records were obtained of over 38 hours of physiological monitoring, involving over 47,000 breaths. The mean respiratory frequency for all flights was 20.5 breaths.min^{-1} and the mean inspiratory minute volume was 18.8L(BTPS).min^{-1}. The data were further analysed for various phases of both routine flight (strapping-in, taxy, take-off, climb, cruise, descent and land) and manoeuvring and applied flight (high G turns, loops, rolls and spirals, aerobatics and ACM). Mean respiratory frequency varied from 19.1 breaths.min^{-1} during routine periods of flight to 22.8 during and immediately after manoeuvres. Mean minute volume was 17.2L(BTPS).min^{-1} and 21.4L(BTPS).min^{-1} respectively during the same activities. Of the 24 individual phases analysed, ACM produced the highest minute volume with a mean of 32.8L(BTPS).min^{-1}. Peak inspiratory flows were also maximal during high G manoeuvres, particularly ACM. Peak flows >150L(BTPS).min^{-1} were seen frequently (7.45% of all peaks) and occasionally (0.25%) reached values >250L(BTPS).min^{-1}. End-tidal carbon dioxide tensions, however, were maximal immediately after entering the aircraft, and just before and during take-off, with a mean of 42.5 mmHg (5.7kPa), and during low level flight (39.1 mmHg (5.2kPa)). Values during manoeuvring flight were inversely related to the magnitude of the acceleration insult, with the lowest levels being recorded during high-G phases (mean: 33.1 mmHg (4.4kPa)). Furthermore, from the beginning to the end of a flight, end-tidal carbon dioxide tensions showed an overall downward trend indicative of mild hyperventilation. Finally, the metabolic cost of flying was derived from the variables studied. The mean overall workload was 85.2kcal.m^{-2}.h^{-1}, while routine and manoeuvring flight produced mean workloads of 82.9 and 89.8kcal.m^{-2}.h^{-1} respectively. Of the individual phases, strapping-in, pre-flight taxying and take-off were routine periods of high workload, with a mean of 96.2kcal.m^{-2}.h^{-1}. This level was only exceeded in the air during ACM, barrel rolls and rolls (means: 160.5, 121.2 and 101.3kcal.m^{-2}.h^{-1} respectively).

All of these findings are discussed and criticised, with emphasis upon the experimental methods, the methods of analysis and the assumptions made. The implications of the results, in the light of previous knowledge and the need for design requirements for future breathing systems, are also considered.

Part 1 - INTRODUCTION

1.1 General Considerations

The physiology of man under various environmental stresses has fascinated scientists since ancient times. Until just 200 years ago, however, those stresses did not include that of acute ascent to altitude, nor indeed other problems of flight such as accelerations, disorientation and, especially, anxiety. The advent of flying machines posed, and continues to pose, challenges for physiology as man has progressed from balloons to propeller-driven and then jet-driven craft; and on upwards, both literally and technologically, to the stars. War machines have, throughout history, developed in parallel with technological sophistication: fighting aircraft are no exception and are now devastatingly potent. Man has become just one small but vital cog in the machinery of high performance flying but little is known of his responses in that environment. Understandably this is because, by the very nature of things, in the design and flying of a small fighting vehicle, at many hundreds of miles an hour at levels from a few hundred to many thousands of feet above the earth, little cognizance is paid to the interests of the physiologist. The physiological needs of the pilot, however, are recognised and heeded as far as practicable; usually as a result of empiricism or extrapolation from ground-based laboratory findings backed by studies at simulated altitudes in decompression chambers. So it is with the respiratory needs of a pilot in flight. Few data are available describing the respiratory responses of man during high performance flight and there is a need for new knowledge upon which the design of breathing systems for future fighting aircraft can be based.

It is intuitively clear that such knowledge is vital, particularly when the increasing sophistication of aerial warfare technology places more and more demands on the pilot. It could be argued that these demands are mental rather than physical and that there can be no doubt that flying a modern jet aircraft is less physically demanding than flying the old 'battle wagons'. But can there really be no doubt? Does the modern pilot, wearing underwear, socks, gloves, anti-g trousers, immersion coverall, flying coverall, boots, helmet and oxygen mask, and perhaps additional protection against chemical warfare agents (Figure 1.1), really work less hard in his cramped and crowded cockpit? The answer is not known. Similarly, it is not known whether or not the breathing systems provided in such aircraft fulfil the true physiological requirements of their users; or, in fact, what those true physiological requirements are. In other words, is the modern pilot being provided with equipment capable of meeting his needs and so allowing him to function as efficiently as possible?

Figure 1.1 Typical modern aircrew equipment assembly (including chemical defence protection)

This study was designed to begin to fill this gap in our knowledge; initially by investigating the 'pure' respiratory responses to flight and then by relating these to the metabolic cost of flying. The following sections review some aspects of in-flight physiological monitoring before discussing these two fields more specifically.

1.2 In-Flight Physiological Monitoring

1.2.1 Early Studies. On the 21st November 1783, Jean-Francois Pilatre de Rozier was one of two people on board the first ever recorded free flight by man.[2] He was also a doctor; and medicine and physiology have retained a close link with flying ever since. The natural curiosity of doctors and scientists has led to a vast knowledge of the effects of flight upon all aspects of human physiology; much of it anecdotal and subjective, all of it of interest. It is only comparatively recently, however, that the difficulties of actually recording physiological variables in flight have been addressed.

Thus, just 21 years ago, Captain James Roman wrote "From 1930, when it was founded, until 1958, inclusive, a total of seven papers were published in the Journal of Aviation Medicine which described electrocardiographic, blood pressure, or respiration data obtained on humans in flight."[3] Some other papers had also appeared in non-english journals but all of these early studies were principally concerned with cardiovascular responses.

In 1931, H von Diringshofen and Belonoschkin measured blood pressure, using an oscillometric method, in inactive subjects while flying in bomber aircraft.[4] In the following year, von Diringshofen and his brother recorded ECG, systolic blood pressure and respiratory frequency using a pneumotachograph, during linear acccelerations of up to 4G. Under these conditions respiratory frequency increased, as did heart rate and systolic blood pressure.[5] Five years later, McFarland and Edwards recorded physiological data from passengers and crew during a trans-pacific flight and concluded that elevation in cardiovascular variables (heart rate and blood pressure) were only seen if the crew was under pressure or at some risk.[6] Respiratory data were not collected, although some attempts were made to determine the composition of alveolar gas. White, in 1940 and again in 1947, studied the effects of mild 'intentional hypoxia' on the ECG during high altitude flights but, again, no respiratory variables were studied.[7,8]

In 1943, Goldie measured respiratory frequency, by means of an electrically triggered telephone counter, throughout a night bomber mission.[9] Both the pilot and the inexperienced observer showed an elevated frequency during the outward journey when compared with the homeward and control levels. Respiratory frequency was also measured during 21 combat missions at the end of World War II by Kirsch.[10] In his narrative account of these flights, which involved 16 subjects including Kirsch himself, respiratory frequency was measured either by counting respiratory movements of the thorax or by counting the rise and fall of the oxygen flow indicator bobbin. These somewhat subjective results revealed a rise in respiratory frequency, pulse rate and blood pressure during times of stress, as, for example, when under enemy anti-aircraft fire. Only one set of figures, for one pilot, was presented. A considerable amount of data, however, was accumulated during the war with regard to oxygen consumption in flight, derived from cylinder oxygen depletion rates, and these studies will be discussed later (p12 et seq). It is of interest to note here that these studies also showed that altitude per se had no effect upon pulmonary ventilation, provided that hypoxia was prevented. In 1949, Narseta made a similar study of 50 airmen during prolonged and hazardous flights over the Arctic in modified bomber aircraft.[11] During flights which averaged 14 hours in length respiratory frequency fluctuated throughout but, despite wide variations, increased on average by 9 breaths per minute over both pre-flight and post-flight levels of 20 breaths per minute. There were concomitant rises in blood pressure and pulse, and a fall in sublingual temperature, throughout the mission. Respiratory frequency was also affected at times of stress, but the method of measurement was not described and no instances of hyperventilation were noted. Again in 1949, Lambert reported a study comparing the responses to acceleration stresses of 24 subjects while on a centrifuge and while as passengers during flights in a 2-seat dive bomber.[12] Although this study was largely concerned with visual symptomatology under high G conditions, it was important because pulse rate was measured at the ear during flight, displayed on a two tube cathode ray oscillograph (together with aircraft acceleration) and recorded by a camera mounted in the aircraft. In the following year, Lambert extended this study to include 16 pilots while either actively flying the aircraft or being flown as passengers.[13]

As a prelude to space exploration, a considerable amount of data was collected throughout the 1950s from high altitude balloon flights. The scientists involved in this programme developed the art of bio-telemetry to the point where accurate radio transmission and interpretation of physiological variables was possible routinely. In 1954, Barr described an early transmitting system, for use in balloons and high performance aircraft.[14] Of interest here is that the system, as well as transmitting information about ECG, EEG and temperature, also delivered respiratory frequency, measured by temperature changes in a thermistor bead placed in the oxygen supply hose and calibrated by spirometry. Respiratory volume could be derived from the measured area beneath the respiratory excursion curve. This first report gave no details of the craft or subjects used in the assessment; nor were any numerical results stated. A similar system was certainly used to good effect, however, in the Man-High high altitude balloon flights during the late 1950s when respiratory frequencies of up to 70 breaths per minute were reported.[15]

An important aspect of these early studies, particularly before the advent of bio-telemetry, was that, with the exception of Lambert's work[12,13], all required the physiological observer and his equipment to be on board the aircraft, which was therefore usually obliged to be a large multi-engined multi-crewed vehicle. With the development of Lambert's instrumented dive bomber began the appreciation of the need for a dedicated test craft if realistic high performance studies were to be made.

Some of the relevant features and findings of these studies are included in Table 1.1 and will be discussed further in Part 4.

Aircraft Type	Study	Date	Ref	n	Variables Studied	Mean Results of Respiratory Studies: Rest f	Rest $\dot{V}_E$	Taxy f	Taxy $\dot{V}_E$	Take-off f	Take-off $\dot{V}_E$	Routine flight f	Routine flight $\dot{V}_E$	Appr & landing f	Appr & landing $\dot{V}_E$	Aeros/Combat f	Aeros/Combat $\dot{V}_E$
Bomber	v Diringshofen	1931	4	3	BP												
Bomber	v Diringshofen	1932	5		BP,ECG,f												
Airliner	McFarland	1937	6	20	BP,HR,alveolar & blood gases												
Bomber/Cargo	White	1940/45	7,8	45	ECG & hypoxia												
Fighter	Penrod	1942	89	8	$\dot{V}_A$												
Bomber	Goldie	1943	9	2*	f							13				27	
Bomber/Fighter	Lovelace et al	1944	85		$\dot{V}_E$												
Bomber	Carlson et al	1944	30		$\dot{V}_E$								18.4				
Multi-engine	Kirsch	1945	10	16*	BP,HR,skin temp,pupil size,f					18		17				25	
Light	Coray	1948	81	3	Metabolic oxygen consumption,f	17				19		18		21			
B29 Bomber	Narsata	1949	11	50	Sub-lingual temp,HR,BP,f	20						28					
2 seat Bomber	Lambert	1949/50	12,13	40	Vision under +Gz,ear pulse												
DC4	Hitchcock	1950	86	10	Metabolic oxygen consumption												
Jet Trainer/Fighter	Balke et al	1956/57	72,73	91	P_ECO_2												
Balloons/Jets	Barr & Voas	1960	15	?*	Telemetered ECG,EEG,temp,f					70							
X-15 Jet	Rowen	1961	19	3	HR,f					32		29		31			
Jets	Holden et al	1962	20		ECG,BP,f												
Jet Trainers	Ellis & Wells	1962	74	31	P_ACO_2 ,urine & blood analyses												
Jet Fighter	Roman	1963	3	3	BP,HR,f			20		19		18		19			
Canberra Bomber	Norris	1964	29	20	$\dot{V}_T$ (derived $\dot{V}_A$),f												
Light	Billings et al	1964	82	20	Metabolic oxygen consumption,$\dot{V}_E$,R								10.5				
Jet Fighter	Roman	1965	23	6	HR,f (not reported)												
Jet Trainer	Lorentzen	1965	90	5	Metabolic oxygen consumption												
Jet Trainer	Roman & Brigden	1966	25	?1	Mass spectrometry (no results given)												
Jet Bomber	Roman et al	1967	27	5	HR												
Jet Bomber	Lewis et al	1967	28	5	HR,f (overall = 29)												
Light	Murphy & Young	1968	35	7	$P_{ET}CO_2$, $\dot{V}_E$ (professionals)				16.5		16.5		14.5		14.5		
				16	(amateurs)				19.0		22.0		15.0		18.0		
Light	Littell & Joy	1969	84	4	Metabolic oxygen consumption,$\dot{V}_E$,HR		10.4		15.6		16.5		10.8		15.1		10.7
Cargo	Kaufman et al	1970	83	18	Metabolic oxygen consumption												
	Ganin et al	1975	75	77	$P_{ET}CO_2$												
Fighters	Morgan et al	1976	38	6	$\dot{V}_E$,f						12.5-23.1		5.0-11.8		28.2		
Transport	Morgan et al	1977	39	8	$\dot{V}_E$,f								12.8				
Jet Trainer	Macmillan et al	1976	42	9	$\dot{V}_E$,$\dot{V}_T$,f								22.0				26.0

* values for one subject only were reported

Table 1.1 Summary of relevant in-flight physiological studies

1.2.2 Studies Since 1958. In 1958, the National Aeronautics and Space Administration (NASA) was established in the United States for the purpose of peaceful exploration of space. There followed a nascency in which interest in in-flight recording blossomed with the inexorable thrust towards safe space flight. Even so, only a further 40 or so papers on the subject have appeared in the Journal of Aviation Medicine (and its descendants - Aerospace Medicine and now Aviation, Space and Environmental Medicine) and only one was concerned solely with respiratory physiology. This single paper, in 1977, described a simple respiratory monitoring device, the main attraction of which was that it was inexpensive.[16] Although it had been used in flight, no numerical results were published and only short examples of the traces obtained were shown. Nothing further has been reported of this instrument. Other studies have, of course, appeared in foreign publications, and as military reports with restricted circulations, but very few have dealt with respiratory physiology alone.

In the United States, several groups of workers have reported their efforts in acquiring physiological data in flight. In the late 1950s, von Beckh (1959) carried out a number of in-flight studies on the effects of zero G (microgravity) upon physiological variables.[17] This series of experiments served to identify and help overcome many of the problems of biomedical monitoring in flight. ECGs were obtained during weightless manoeuvres and during high levels of positive acceleration. Ware and his colleagues also refined the automatic measurement of blood pressure during this period, using an occlusive technique and gated microphone[18], but problems of sensitivity to noise and to motion artefacts continue to bedevil this field. There is still no reliable non-invasive means of continuous monitoring of blood pressure in flight. In 1961, Rowen described the bio-medical monitoring of test flights in the X-15 high-altitude, high-speed, rocket-powered research aircraft.[19] A pneumotachometer, installed in the pilot's oxygen system and connected to an on-board recording oscillograph, was used to confirm telemetered respiratory data. Unexpectedly high cardiac rates and respiratory frequencies (over 140 beats and 30 breaths per minute respectively) were seen prior to launch, during burnout and on landing: affects which were ascribed to the 'stress' factor of flight. Holden at al, in 1962, described a complete system for the measurement of ECG, pulse rate, blood pressure and respiratory frequency in high performance aircraft.[20] Again, blood pressure was measured using an autosphygmomanometer while respiratory frequency was determined with a pneumotachograph (site not specified). A more sophisticated system, as in Lambert's work [12], was used for comparison work on a centrifuge. It is interesting to note that an infra-red carbon dioxide analyser was used in this centrifuge system but was "too large to be installed in the test aircraft". Although some informative graphs were published with this description, no numerical values were reported and no details were given of the subjects used. Furthermore, while the possibility of using the respiratory frequency trace to determine respired volume was mentioned, there is nothing to suggest that this derivation was attempted.

Also in 1962, Roman and colleagues, based first at the United States Air Force School of Aerospace Medicine (USAFSAM) and then at the NASA Flight Research Centre, published the first of a series of papers describing physiological studies in high performance aircraft. Specifically, these studies involved the use of fully instrumented and dedicated test vehicles, the need for which has already been established. Two modified 2-seat NF-100F jet aircraft were made available for this team's work as a consequence of the space programme and the need to study the effects of weightlessness. The first paper described the philosophy behind in-flight data gathering and identified several main purposes for such research.[21] At that time, these purposes were mainly concerned with the space programme but one, the determination of physiological norms for human subjects in flight, was particularly relevant to the present study. The paper also addressed the technical problems of in-flight instrumentation. Once again, however, there is no mention of numerical results or indeed of the numbers of subjects and flights assessed. Respiratory frequency was measured by a heated thermocouple sensor fitted within the quick disconnect of the oxygen mask hose. The device was stated to have zero resistance to flow and to be independent of motion. Output was logarithmic and would have required computer analysis to derive respiratory volumes: consequently, this was not attempted.

In 1963, however, Roman did publish the results of a study of three pilots over almost one year during which in-flight blood pressure, ECG and respiratory frequency were correlated with flight data in various situations.[3] Blood pressure was measured by the acoustic cuff method of Ware and Kahn[14] while respiratory frequency was again measured by a heated thermocouple transducer mounted in the subject's oxygen hose. In later studies, a heated thermistor was used instead. Minute volume was not derived because of the work involved in reducing the logarithmic output of these devices. In-flight variables were recorded on a 50-channel oscillograph mounted in the aircraft and which provided over 1½ hours of continuous recording. Results from 9 'boredom' or control flights and 18 'cro country' or experimental flights were presented. It was concluded that responses in heart rate, blood essure and respiratory frequency were highly reproducible in the same individual and in similar flight circumstances, and that values for all three were elevated when compared with basal levels (in fact, no basal levels for respiratory frequency were given). Notwithstanding the small number of subjects involved, this work was an important step forward in the attempt to correlate physiological responses with various in-flight situations.

Thereafter, between 1965 and 1967, Roman and his co-workers published a series of fourteen papers, of which only six were directly relevant to this review, under the umbrella title of 'The Flight Research Program'. As before, much of the written word was concerned with theoretical and practical aspects of the need for such research and the problems of instrumentation, which again was primarily directed towards collection of cardiovascular data. The first paper described the Research Program and its ambitious goals, based upon three main areas: research on physiological variables using a large student population, development of advanced instrumentation and development of computer techniques for analysis.[22] This prospective report contained no results or findings but did give a tantalising picture of the intended scope of this project including the possibility of an airborne mass spectrometer, measurement of oxygen consumption, high impedance electrode techniques, vibrocardiography and pulse wave velocimetry. None of these possibilities has yet borne full fruit in high performance aircraft although some aspects were expanded theoretically and practically later in the series. The second paper described the results of 37 flights in 2-seat F104B fighter aircraft, in which both pilots were instrumented for ECG and respiratory signals using a Project Gemini prototype signal conditioner.[23] Aircraft variables (acceleration, altitude, airspeed, angle of attack and sideslip) were also recorded on an on-board photographic oscillograph. Despite apparently recording respiratory data, no comment whatever was made on respiratory variables during these high performance flights. On the other hand, an important conclusion was that physical risk or danger did not seem to be the factor primarily responsible for the high heart rates seen in such flights; rather, responsibility for the mission appeared more relevant.

A small (12.7 kg (28lb)) mass spectrometer, with a fast response time and capable of simultaneous and continuous monitoring of up to 12 gases, was described in the fourth paper[24] and a single, apparently successful, test flight briefly reported in the fifth together with a general discussion on mass spectrometers and their use in aerospace medicine.[25] Nothing more of this attractive and potentially most important development has appeared in the open literature and it has been suggested that the vacuum supply pack and supporting equipment were too heavy and bulky for use in high performance aircraft.[26] The seventh paper reported the results of the first automated monitoring of aviators during combat in South-East Asia.[27] A seven-channel body-borne type of tape recorder was used but actually mounted in the aircraft map pocket for reasons of safety. Only heart rate and aircraft acceleration were recorded although the facility to record respiratory frequency and voice was available and used in later flights. Nine flights yielded usable data and confirmed earlier findings that neither risk nor danger were the major factors determining heart rate in experienced pilots under moderate non-physical stress. This study was important in one other relevant aspect, in that attention was paid to the possible implications of ejection. This was the first occasion on which safety factors were mentioned. Special attachments to the parachute harness were designed to provide for automatic disconnection of all electro-physiological leads should the pilot eject. The need for, and design of, such safety features was of major importance in the present study (p24). The ninth paper in this series, and the last of direct relevance to this discussion, reported a subsequent and similar study of pilots during combat flying.[28] Voice and respiratory frequency were recorded on this occasion, as well as heart rate and aircraft acceleration. Respiratory frequency was measured by means of a pneumotachometer mounted in the oxygen hose. Technical problems with this device meant that only thirteen hours of intermittent recordings were usable from the 18 flights monitored and discrete analysis of respiratory frequencies during launch, bombing and recovery was not possible. The overall frequency was 23 breaths.min^{-1}. It was noted, however, that breath-holding frequently occurred during launch, and during anti-g trousers inflation, and was followed by deep slow breathing.

Some of the relevant features and findings of these studies are included in Table 1.1 and will be discussed further in Part 4.

From about this time onwards, in-flight physiological monitoring during high performance flight began to include the acquisition of respiratory data beyond that of simple frequency. It must be emphasised that the measurement of respiratory frequency alone is of little value since it is knowledge of the turnover of gas in the alveoli which is needed. This can be approached more closely by measuring both frequency and tidal volume.

1.2.3 Respiratory Physiology in Flight. Several areas of respiratory physiology are legitimately the concern of those involved in aviation medicine. Such areas include studies of:

Respiratory frequency, minute volume and peak flow,

Added external resistance,

Hyperventilation,

and the Metabolic cost of flying.

1.2.3a Respiratory Frequency, Minute Volume and Peak Flow. Apart from those studies described above, in which respiratory frequency was measured either subjectively by watching the rise and fall of the chest (or the movement of an oxygen flow meter) or objectively by a thermocouple/thermistor in the inspiratory supply hose, very few other reports have been published giving details of respiratory frequency, minute volume or instantaneous flow.

In 1964, however, Norris reported the results of a study of 20 pilots flying Canberra jet bombers during 21 training flights.[29] Respiratory frequencies and minute volumes were recorded continuously; the former by means of a simple counter linked to the magnetic flow indicator of the oxygen regulator, and the latter by means of an anemometer. Mean respiratory frequency was 17 - 18 breaths per minute and mean pulmonary ventilation was reported as 13 - 14L(BTPS).min^{-1}. Although discrete analysis of these variables during various phases of flight (such as take-off, overshoot, GCA and landing) was carried out, no significant variation in the mean values was demonstrated. These figures correlated very well with previously published wartime values for the pulmonary ventilation of aircrew, based on bottle oxygen consumption (ie calibrated reservoir, pressure drop) techniques and not on direct physiological observation. It should be noted that figures calculated in this manner incorporate an oxygen leak of unknown magnitude. In two such American studies and one British, average values for 'resting' aircrew ranged from 10.0 - 12.9L.min^{-1} and for aircrew in simulated combat from 21.6 - 36.0L.min^{-1}.[29] Carlson et al[30], in 1943, had determined the 90% requirement (that is, the volume required by 90% of the population) for inactive bomber crews to be 18.4L(BTPS).min^{-1} while 18L(BTPS).min^{-1} had been recommended as the United States Army Air Force standard.[31] The United States Navy reported a higher figure of 23.7L(BTPS).min^{-1} during in-flight studies of moderately active aircrew[32] and a report in 1960 had recommended similar figures for a design standard: values of 25.1L.min^{-1} to embrace the needs of 95% of the population, with a mean of 12.6L.min^{-1}.[33] Norris's study[29] was also of importance in that comment was made with regard to the added external resistance imposed by the breathing system upon respiration, and to its possible effects, (p9). Finally, Norris reported that, from derived values of alveolar ventilation, high respiratory frequencies were often associated with a reduction in pulmonary ventilation. He concluded that a diagnosis of hyperventilation based on respiratory frequency alone was invalid, (p11).

In 1965, Ernsting wrote that "Oxygen equipment must be capable of meeting the pulmonary ventilation requirements of aircrew both on the ground and in flight."[34] He went on to explain the importance of knowing the magnitude and form of breathing patterns under all conditions. At that time, based upon the 1940s studies described above[29,30] and others, he summarised the respiratory minute volumes of aircrew free of hypoxia under various conditions of flight thus:

Seated Inactive	10 - 15L(BTPS).min^{-1}
Seated Active	15 - 25L(BTPS).min^{-1}
Mobile	25 - 40L(BTPS).min^{-1}
After running to aircraft	up to 100L(BTPS).min^{-1}

Norris's own figures[29] clearly correlate well with these consolidated data although the wide individual variation in responses noted by him must be emphasised.

In 1968, Murphy and Young made a careful study of 25 pilots (amateur and professional) flying light aircraft at low altitudes.[35] The study was primarily concerned with the incidence of hyperventilation in flight by a consideration of end-tidal carbon dioxide tensions (p11), but expiratory minute volumes were also measured by means of a Wright respirometer (a compact turbine type spirometer) mounted in the cockpit. Altitude was maintained at or below 1,200 feet (366m) to minimise changes due to air density. A clear difference between amateur and professional pilots was demonstrated, with the former ventilating more during all phases of flight. In addition, higher minute volumes were seen in non-current pilots (cf current), in first flights of the day and in the early stages of a trip (taxy, take-off and climb). Some of these results are included in Table 1.1 (p6).

Little else was reported in this field for eight years, when a series of technical reports and military papers appeared describing respiratory measurements in high performance aircraft in an attempt "to better define breathing system design parameters."[36]

In the United States, Morgan et al from USAFSAM described the development and use of a so-called In-Flight Data Acquisition System (IFDAS).[36] This ambitious project, apparently a continuation of Roman's work, entailed the continuous and simultaneous recording of expiratory flow (and hence respiratory frequency, minute ventilation and tidal volume), inspired-expired oxygen concentration difference, ECG, aircraft acceleration, cabin pressure, voice and time index. Expiratory flow was measured by a differential flow transducer and the oxygen concentration difference by twin polarographic oxygen sensors.[37] No oxygen concentration results have been published but preliminary findings for expiratory volumes in both fighter[38] and transport[39] aircraft were reported in 1976. The data were analysed for various in-flight situations - taxy, take-off, climb, cruise, descent, approach and landing - and some of these results are summarised in Table 1.1. The important conclusion drawn from both of these papers was that measured values frequently exceeded those stated as acceptable for the design performance of aircraft breathing systems and this was most obvious during the take-off and landing phases. A consolidated and enlarged report was published in the following year confirming the earlier findings but adding no new information.[39] In 1979, the IFDAS was again described in a military publication; this time recording inspiratory flow, heart rate and skin temperature in addition to those variables monitored previously.[40] The complicated mask assembly, incorporating either a differential flowmeter or an ultrasonic flowmeter and an oxygen sensor, as well as the supporting in-flight and ground-based equipment was under evaluation in the laboratory at that time. Nothing further has been reported of the system and the project is now believed to be in abeyance.[41]

In the United Kingdom, a single paper by Macmillan et al in 1976 reported the results of a similar study to that of Morgan et al[38], but in this case using a dedicated test aircraft (the same one as was used in the present study).[42] The impetus for this work was the development, in the Royal Air Force, of new breathing systems for use in a chemically contaminated environment and the need to confirm existing system design requirements. Inspiratory flow, inspired gas temperature, cabin altitude and aircraft acceleration were monitored and recorded on an on-board magnetic tape recorder. Nine pilots were studied, using a standard breathing system, during aerobatic manoeuvres: a mean pulmonary ventilation of 26L(BTPS).min^{-1} was reported with a mean peak inspiratory flow of 116L(BTPS).min^{-1}. Peak flows in excess of 150L(BTPS).min^{-1} and pulmonary ventilations exceeding 40L(BTPS).min^{-1} were recorded infrequently and were not sustained. The study also revealed a significant difference between those actively controlling the aircraft and those experiencing the manoeuvres passively as passengers, a finding which supports Roman's cardiovascular studies.[33]

The present study may be regarded as an extension of this British work.

<u>1.2.3b Added External Resistance</u>. Interestingly, none of these more recent studies, apart from that of Norris[37], and certainly none of the earlier reports, even commented upon the added external resistance to breathing imposed by the system in use although this undoubtedly has an effect.[34] And, indeed, several reports appeared during the war describing subjective resistance standards for oxygen equipment.[43] The added external resistance of any breathing system should be as low as possible and, ideally, should be zero. That this is not possible practicably has long been recognised in the technical specifications for breathing systems in use with aircraft of Western air forces, (p15 et seq).

In this discussion, the term **added external resistance** will be used to describe the additional pressure imposed by a breathing system, and present throughout the entire respiratory cycle, for a given flow or instantaneous peak flow. This has long been regarded as a convenient relationship for respiratory equipment, particularly when pressure tends to be related linearly to flow. Numerical expressions will therefore be negative during inspiration and positive during expiration, and will describe the pressure swing or change at the mouth of the user.

No in-flight studies have been carried out with specific regard to either the magnitude or effects of added external resistance but it is entirely reasonable to suppose that such effects as seen in the laboratory will be at least as great in the air. Thus, a brief consideration of the effects of added resistance upon respiratory variables is appropriate here; particularly since Ernsting has stated that "In laying down the physiological design criteria for oxygen equipment, the respiratory minute volume is of lesser importance than is the maximum instantaneous flow ...... The flow of air in and out of the respiratory tract changes very rapidly, and respiratory equipment must be capable of responding to these changes with the minimum of flow resistance." [34]

In 1943, Silverman et al photographed the displacement of a fine platinum wire, with no appreciable resistance to flow, in order to study the inspiratory flow patterns of individuals working at different levels of activity and breathing against various degrees of external resistance.[44] Analysis of the respiratory patterns obtained at minimum resistance (<5 mm water (0.05kPa) at 100L.min^{-1}), revealed the following features:

> <u>At rest</u>: Inspiration starts with a rapid increase in flow to about 25L(BTPS).min^{-1} over 0.1 - 0.3 sec and then rises more gradually to a peak of about 32L(BTPS).min^{-1}. Air flow then falls to zero at the end of inspiration, the whole taking 2 - 3 sec. Expiration follows immediately, lasts longer, but has a lower peak. The ratio of peak inspiratory flow to minute volume is about 3:1.
>
> <u>During Moderate Exercise</u>: Respiratory minute volume increases as a result of both increased respiratory frequency and increased tidal volume. The duration of each phase is shortened (expiratory more than inspiratory) and so peak flows increase, as do rates of change. The ratio of peak inspiratory flow to minute volume decreases to about 2.5:1.
>
> <u>During Heavy Exercise</u>: The duration of the expiratory phase of the respiratory cycle may be less than that of the inspiratory phase.

The addition of resistance to breathing alters the shapes of these patterns dramatically and has increasingly obvious effects on respiration. These effects were first described by Davies et al in 1919[45], when it was found that imposed pressure swings at the mouth of +/- 10 cm water (+/- 0.98kPa) caused a slowing and deepening of respiration with carbon dioxide retention. Raising the external resistance further changed the breathing pattern from slow and deep to rapid and shallow; the change occurring when normal inspiratory peak flow was halved. Subjective feelings of asphyxia accompanied this imposition. Later, Killick found that carbon dioxide retention also occurred if resistance was imposed during inspiration only[46], and its accumulation was said to be responsible for the symptoms of distress seen during resistance breathing. Hart, in 1946[47], established that subjective feelings became apparent, during quiet breathing, when the pressure fluctuation at the mouth exceeded about 16 mm water (0.16kPa), and were uncomfortable by the time resistance reached 35 mm water (0.34kPa). He also demonstrated that the ratios of peak inspiratory and expiratory flows to pulmonary ventilation decreased as breathing resistance increased. It is of interest to note that the highest peak inspiratory flow recorded in this study was 194L.min^{-1} after very heavy exercise. Later studies described the changes seen when resistance was added during inspiration alone, during expiration alone or during both (as in aircraft breathing systems). Ernsting has criticised these experiments as being of too short a duration, but summarised the results as showing that imposition of external resistance in either or both respiratory phases causes a fall in minute volume which is greatest when both phases are affected.[34] Imposed resistance also reduces the rate of change of, and peak, air flow and prolongs that phase which is being compromised. Predictably, the phase which is unaffected behaves normally, at least at first.

Further investigations in the 1960s and 1970s confirmed and refined the findings of this early work both with respect to the level of detectable resistance and with regard to the physiological consequences of added external resistance. These studies were principally concerned with either the performance of open circuit respiratory protective devices, such as those used in contaminated environments, or with the possible implications of findings in healthy subjects for those with obstructive airways disease.

Campbell and his colleagues, in 1962, found that, during quiet breathing, inspiratory-expiratory loads with a mean of 0.59 cm water.L^{-1}.sec^{-1} (0.06kPa) were detectable.[48] The ability to so detect was ascribed to a variation in normal perception of pressure-volume relationships or what they termed 'length-tension inappropriateness'. Newsom Davis was later (1967) to conclude that such perception depended upon somatic receptors in the chest wall, and specifically the thoracic joint receptors.[49] Other groups of workers have assessed the overall additional cost, in terms of work, of added respiratory resistance. In 1965, Tabakin et al confirmed earlier findings of reduced minute volume, oxygen utilization and carbon dioxide elimination when expiratory resistance was raised, but also described unpredictable changes in cardiac output and central blood volume.[50] They concluded that the imposed external resistance was modifying gas distribution in the lungs and compromising ventilation-perfusion ratios. Later work, by the same group, revealed a decrease in lung compliance associated with resistance breathing which, it was believed, confirmed the occurrence of alterations in pulmonary blood volume.[51] In 1966, Thompson and Sharkey also demonstrated reduced oxygen utilization associated with external respiratory loads, and related recovery of this oxygen debt to the level of air flow resistance, particularly at high workloads.[52] Cerretelli et al, in 1969, concluded that the ventilatory responses to exercise when airway resistance is elevated (in this case considerably: up to -60/+46 cm water (-5.88/+4.5kPa)) are due to a combination of decreased minute volume and increased work of breathing; and while maximum oxygen uptake and the capacity for muscular work are reduced in a manner directly proportional to the added resistance, the relationship between oxygen uptake and workload is unchanged.[53] Craig et al (1970) related time to exhaustion directly to the magnitude of imposed resistance.[54] Again, however, these experiments were of short duration and involved few subjects. Similarly, a study by Demedts and Anthonisen (1973) on the effects of respiratory loads during steady-state exercise covered periods of exercise of up to only five minutes.[55] Nevertheless, the authors concluded that "The resistances of breathing circuits, if they are not very high are not critical in determining ventilation during steady-state exercise". "Not vary high" in this context presumably meant less than +/-40 cm water (+/-3.9kPa) at 6L.sec^{-1}, since this resistance caused only a 12% decrease in ventilation during maximum exercise. Maximum exercise capacity was always achieved with added loads up to that level while ventilation was grossly reduced and maximum work level limited above it.

It is a consistent criticism of all these studies that there appears to be little uniformity, if any, with regard to the way in which imposed resistance is expressed. Often, the very resistances under study are either not defined or appear only as graphs of pressure-flow characteristics. Inevitably, comparisons between studies are difficult, if not impossible. Despite this lack of useful quantitative material, the overall effects of added resistance are well-established and are summarised in Figure 1.2.

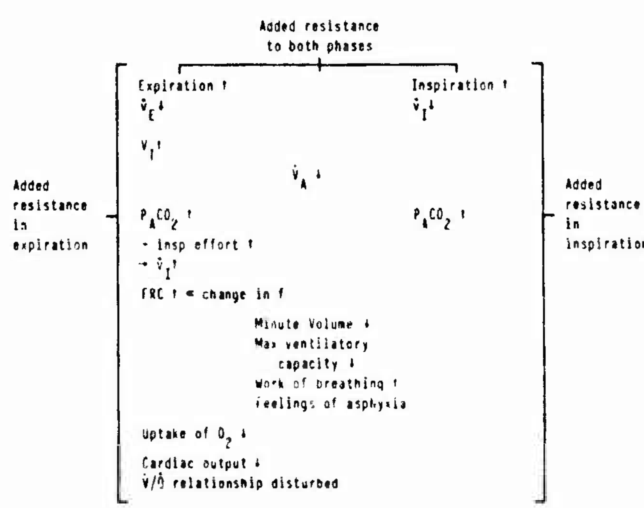


Figure 1.2 The physiological effects of added external resistance to breathing upon cardio-respiratory function

The magnitude of acceptable levels of breathing resistance, as applied to aircraft systems, will be discussed later (p15 et seq).

It is clear, therefore, that added external resistance is an undesirable but inevitable feature of any breathing system. This is not only because of the effects discussed above but also because, although hypoventilation is the normal response, to complicate matters further, "There is little doubt that, in susceptible subjects, the addition of resistance to breathing can cause hyperventilation with a consequent hypocapnia."

1.2.3c Hyperventilation. Hyperventilation may be regarded as pulmonary ventilation greater than that required to maintain normal carbon dioxide tensions in the body. The symptoms and signs of hyperventilation are entirely attributable to the resulting respiratory alkalosis. They are well-known, and include lightheadedness, feelings of unreality, anxiety, paraesthesiae, visual disturbances and palpitations; but their diversity leads to difficulties with clinical diagnosis. Such symptoms commonly occur when P_ACO_2 falls to 20 - 25 mmHg (2.66 - 3.33kPa), while tetany, or even unconsciousness, although rare, may be expected if P_ACO_2 falls below 15 mmHg (1.99kPa). Of the many causes of hyperventilation, those of particular relevance to aviation may be summarised thus:

a. Environmental Causes. It has long been known that **hypoxia**, including acute hypobaric hypoxia, stimulates respiration and much evidence has been presented to elucidate and confirm the underlying mechanism of increased peripheral arterial chemoreceptor discharge.

Sinusoidal vertical **vibration** at up to 10 Hz, such as might be experienced in aircraft during turbulent flight, has been shown to produce hyperventilation probably as a result of discomfort, labyrinthine stimulation and the addition of oscillations upon the respiratory tract and abdominal contents.

Thermal stress, in the form of exposure to both hot and cold environments has been shown to cause hyperventilation. Thus, an increase in deep body temperature was accompanied by a rise in tidal volume but a fall in respiratory frequency. The increase in pulmonary ventilation was only accompanied by a fall in $P_{ET}CO_2$ when deep body temperature had risen 1.5°C. Immersion in cold water at temperatures of 29°C and 10°C produced a rise in respiratory frequency and a fall in $P_{ET}CO_2$, the changes being more severe at the colder temperature. Like changes occurred during moderate exercise in cold water, but heavy exercise produced a smaller reduction in $P_{ET}CO_2$ and resembled the findings in warm water.

b. Psychological Causes. In healthy subjects fear, anger, pain and extreme emotion have all been quoted as potent causes of hyperventilation, possibly as a result of adrenaline and noradrenaline release as part of the 'Flight or Fight' reaction. Anxiety is probably the most potent cause of hyperventilation in flight, (p12).

c. Pharmacological and Pathological Causes. Drugs, such as salicylates and analeptics, may stimulate respiration as may disease states including pulmonary disease, anaemias and pyrexias. None of these is likely to affect aircrew in flight, however, unless they are already ill and self-medicating.

d. Instrumental Causes. As described above, added external resistance to breathing may produce hyperventilation in susceptible individuals, although hypoventilation is the normal response. An extreme case of added expiratory resistance occurs during pressure breathing without counter-pressure, when such a manoeuvre at 30 mmHg (3.99kPa) may reduce P_ACO_2 to 28 mmHg (3.73kPa).

No matter what the precise cause of hyperventilation, the potential for disaster is obvious if it develops in a pilot while flying his aircraft.

In 1941, the first description of a case of hyperventilation in flight was published by a group of workers from the Mayo Clinic. Over the next few years, the same group reported further incidents, discussed their causation and management, and declared hyperventilation to be a potential hazard for aircrew, thus supporting an original suggestion made over 20 years earlier by Briscoe. From that time, however, as Gibson (1979) pointed out in a review paper, opinion was divided as to the importance and incidence of hyperventilation in flight. Many workers, analysing routine flight data, and that from incidents and accidents, found a very low incidence of hyperventilation, while other groups reported a relatively high frequency. Interestingly, the former group tended to be those examining evidence retrospectively while the latter attempted to measure PCO_2 quantitatively. Thus it seems that an objective diagnosis of hyperventilation is not necessarily accompanied by the subjective appearance of symptoms and signs. A summary of these studies is at Table 1.2.

Of particular relevance to the present study were the attempts to measure PCO_2 in flight. Balke et al and Ellis and Walls used similar equipment to measure mixed expired carbon dioxide tensions. Four separate samples were collected into gas sampling tubes via a mixing bottle at various stages during each flight. They were then analysed on the ground by either the Haldane technique or an infra-red analyser. The assumption was made that mixed expired tensions were the same as alveolar tensions; the maximum error in this assumption being stated as +/-5 mmHg (0.66kPa). This somewhat glib assertion paid no account to the changing relationship between dead-space and tidal volume, and Gibson estimated the error to be considerably greater than 5 mmHg (0.66kPa) at normal minute volumes, although it decreased as minute volume rose. The assumption was therefore grossly erroneous and may account for the high incidence of hyperventilation reported by these authors. Notwithstanding this criticism, Balke's group did claim a significant incidence of hyperventilation at all levels of pilot expertise. Furthermore, the incidence increased significantly as the performance of the aircraft increased. The role of experience, and indeed of the level of practice, even on the same flight, was demonstrated by Murphy and Young in 1968, but this time most clearly on minute ventilation rather than carbon dioxide tensions (p8). Indeed, the latter, measured as end-tidal PCO_2 with an on-board infra-red analyser, remained normal in nine of the ten pilots studied and even the exception did not lower his $P_{ET}CO_2$ to a symptomatic level. These conclusions supported those of Norris four years earlier in that a diagnosis of hyperventilation based on respiratory frequency alone was invalid. Norris had proposed the measurement of $P_{ET}CO_2$ as the next stage in his own research. Genin et al, in 1975, used a discrete sampling technique for $P_{ET}CO_2$ tensions, but their results (low resting values of 32 - 24 mmHg (4.27 - 3.12kPa)) probably reflect mixing of the expirate and must cast some doubt on the validity of their in-flight findings.

Study	Date	Ref	Accidents/ Incidents reviewed		Routine Flights reviewed	Number of events attributed to Hyperventilation
RETROSPECTIVE						
Konecci	1956	67	73			8
Konecci	1955	68	286			0
	1956	67	332			4
Mullinax & Dion	1958	69			40	0
Talbot	1958	71	620			27
Rayman	1973	70	89			1
Rayman	1983	77	146			10
			A/C Type	Measured	Subjects & Flights	Incidence of Hyperventilation & rationale
PROSPECTIVE						
Balke et al	1956	72	T33	P_ECO_2	26 in 85	42% < 20mm Hg
Balke et al	1957	73	T33	"	29 in 125	41% < 30mm Hg
			F86	"	19 in 64	63% < "
			F100	"	17 in 14	78% < "
Ellis & Wells	1962	74	T33	"	31	39% < "
Murphy & Young	1968	35	Light	$P_{Ei}CO_2$	10	Nil
Genin et al	1975	75		"	77 in 172	Mean fall of 5mm Hg with further falls at times of stress

Table 1.2 Summary of studies of the incidence of hyperventilation in flight

That hyperventilation occurs in flight is not disputed and it has been cited as a possible and probable cause of many incidents. In 1983, in a 10 year review of 146 cases of sudden in-flight incapacitation in military aircrew, Rayman attributed ten to hyperventilation associated with anxiety; all of which occurred in trainees.[77] Ernsting and Sharp (1978) have stated that 20 - 40% of student aircrew are believed to develop symptomatic hyperventilation at some stage during their flying training, while experienced aircrew are certainly not immune.[16] But there is clearly a need to establish, reliably, the incidence of hyperventilation during high performance flight. Gibson had concluded the same in 1979[14], but realised that operational constraints precluded the use of any invasive technique. He recognised that "The ideal way would be to measure in-flight $P_{ET}CO_2$", but technology at that time was not capable of so doing.

While the above account has dealt primarily with the incidence and effects of acute hyperventilation in flight, it is also of importance and interest to establish whether prolonged mild hyperventilation occurs during a long and demanding mission; and, if so, what are its implications, particularly with regard to performance. Such mild hyperventilation was first suggested as a possible cause of in-flight problems by Hinshaw et al in 1943.

1.2.3d The Metabolic Cost of Flying. The magnitude of carbon dioxide production in flight clearly has other implications, beyond those of hyperventilation, for it is one means of assessing the metabolic cost of flying. Such knowledge, in turn, is of importance for the design and performance of aircraft and personal conditioning systems. Once again, however, there is a paucity of information concerning the energy expenditure of pilots in all types of aircraft and especially in high performance vehicles.

Although information does exist concerning the energy cost of performing a wide range of activities, Passmore and Durnin, in 1955, were only able to find one report of measurements made in flight.[78] Twelve years later, in a follow-up study, the same authors stated that no further airborne studies had been conducted.[79] In fact several studies had appeared in the open literature by that time and several more have appeared since. In 1971, a review of the available literature by Sharp et al provided a very useful account and analysis of the then state of knowledge.[80] These authors chose to distinguish between studies concerned with lightweight aircraft (single and twin engined), multi-engined heavy aircraft, helicopters and high performance aircraft: this approach is also used here, along with a consideration of some ground-based aspects. Similarly, their expression of energy expenditure in units of $kcal.m^{-2}.h^{-1}$ for all results (which involved conversion of some published figures) to allow for comparability was most useful, and has been perpetuated. Numerical values for the studies discussed are consolidated in Table 1.3.

Aircraft Type	Study	Date	Ref	n	Mean values of energy expended ($kcal.m^{-2}.h^{-1}$) for aircrew during:										Notes
					Basal	Rest	Taxy	Take-off	Routine flight	Approach & landing	Aeros	Combat	Emers	Hover	
Fixed-wing Light															
Piper J3	Corey	1948	81	3		50			81 - 91						
Piper Apache	Billings et al	1964	82	20		44			55	64					
Piper/Cessna	Murphy & Young	1968	35	25					95						*
OH Beaver	Littell & Joy	1969	84	4	32	53	81	84	54	75	53				
Fixed-wing Heavy															
WW II	Lovelace et al	1944	85						64			58			Pilots*
									105			94			Others
DC 4	Hitchcock	1950	86	10		45			(90)						
C-123	Kaufman et al	1970	83	2		52			51				58		
C-131				8		49			54				68		
KC-135				8		42			44				78		
Helicopters															
OH-6A (light)	Littell & Joy	1969	84	8	36	53		64	49					67	
UH-1B (medium)				8	37	50		53	49					55	
CH-47A (heavy)				7	37	48		62	52					62	
J-CH3 (heavy)	Kaufman et al	1970	83	9		51			49				69		
UH-12 (light)	Billings et al	1970	87	4		48		85	73					97	
Gazelle (light)	Thornton et al	1983	88	6		43			61					68	**
Puma (medium)				6		59			94					111	**
Fixed-wing High Performance															
Ww II Fighter	Pearod	1942	89	8		46			46				65		*
WW II Fighter	Lovelace et al	1944	85						52			81			*
T33 Jet Trainer	Lorentzen	1965	90	5		46			52		98				
[F-9F simulator]	Tiller et al	1957	91	9		50		66	59	65		78		72	
Means					36	48	81	66	62	66	78	78	69	74	

* Figures computed by Kaufman et al[83] from $\dot{V}_E$ (see text) ** Assumes mean body surface area of $1.8m^2$

Table 1.3 Summary of studies of energy expended by aircrew during flight in various aircraft types

Lightweight Fixed-Wing Aircraft. In 1948, Corey measured the oxygen consumption of three pilots, of differing experience, in a single-engined aircraft.[81] Oxygen consumption was measured by mounting an oxygen-filled spirometer in the aircraft and observing its depletion. Higher energy expenditure was seen in the two less-experienced pilots and was attributed to an increase in muscular tension as a result of anxiety, rather than to any extra muscular effort needed to fly the aircraft. Sixteen years later, using an open circuit method, Billings et al measured the oxygen consumption of 20 experienced pilots during the final stages of flights in a twin-engined aircraft.[82] The execution of an instrument approach pattern resulted in a 45% increase in energy expenditure over resting levels ($64kcal.m^{-2}.h^{-1}$ cf $44kcal.m^{-2}.h^{-1}$). In 1968, Murphy and Young attempted to clarify the incidence of hyperventilation in pilots of light aircraft, (p11).[35] Their measurements of pulmonary ventilation were used by Kaufman et al, in 1970, to derive oxygen consumption.[83] Several assumptions were made for these derivations including a respiratory exchange ratio of 0.83, a mean body surface area of $1.8m^2$ and a caloric equivalent for oxygen of 4.83. A relatively high mean value for energy expenditure ($95kcal.m^{-2}.h^{-1}$) was not explained but may have been due to the marked differences seen between inexperienced and experienced subjects in this study. Although this difference was suggested by Corey's study [81], it was not confirmed by other work, including that of Kaufman et al. [83]

In 1969, Littell and Joy, in a study which included one fixed wing aircraft as well as three types of helicopter, measured oxygen consumption from expired minute volume and expired oxygen tension using a gas meter and a paramagnetic oxygen analyser (ie an open circuit technique).[84] They also recorded ECG in flight. Their results clearly demonstrated increased energy expenditure at times of high physical activity (take-off and landing) compared with routine flight. During the landing phase, energy expenditure was somewhat higher ($75kcal.m^{-2}.h^{-1}$ cf $64kcal.m^{-2}.h^{-1}$) than that found during the same phase by Billings et al[82] almost certainly because of differences in the physical effort needed to fly the aircraft involved.

Heavy Fixed-Wing Aircraft. Metabolic oxygen consumption, derived from wartime values of pulmonary ventilation reported by Lovelace et al in 1944[85], was again computed in the study by Kaufman et al.[83] In addition to the assumed values used in the similar treatment of Murphy and Young's paper[35], it was assumed that no hypoxic stimulation to breathing had occurred and, to that end, only those data related to flights below 10,000 feet (3,048m) were used. From these calculations, mean energy expended by pilots during routine flight and combat was said to be 58 - $64kcal.m^{-2}.h^{-1}$ and by other, more active, aircrew (eg gunners) 94 - $105kcal.m^{-2}.h^{-1}$. Interestingly, for both groups, the lower figure represented that in combat. In 1950, Hitchcock, using an open circuit technique, reported that energy expenditure approximately doubled during routine flight and manoeuvres when compared with resting values.[86] Numerical values in flight were not given.

Kaufman et al[83], as well as deriving and comparing results from earlier studies, such as that of Murphy and Young[85] and Lovelace et al[86], measured oxygen consumption themselves, again using an open circuit technique, in three types of heavy cargo aircraft (and one large helicopter) during routine flight and simulated emergencies. Their results compared well with previously reported findings and they concluded that energy expended by pilots during routine flight in heavy aircraft was little greater than that expended at rest. Furthermore, pilot experience did not seem to affect energy expenditure in this type of aircraft.

Helicopters. The studies by Littell and Joy[84] and by Kaufman et al[83] both included measurements on the pilots of four different types of helicopter with markedly different flying characteristics and complexity. Despite this, results for all four types were remarkably consistent: the most energy-demanding phases of flight were emergency situations and hovering close to the ground. Billings et al, also in 1970, confirmed the close hover as the most demanding phase of normal helicopter flight, but consistently recorded higher energy expenditures in flight than either of the other studies.[87] This was attributed to the presence of more sophisticated control systems in the latter. In 1983, Thornton et al used the Oxylog to measure oxygen consumption and inspired volume in two types of military helicopter.[88] Their results showed that the mean energy expenditure for both types in level flight was 50% higher than that when sitting at rest, and that there was a 15% increase over level flight energy expenditure when hovering.

High Performance Fixed-Wing Aircraft. Kaufman et al[83], using the same procedures as before when dealing with previous work, derived the metabolic oxygen consumption of pilots flying World War II fighters, from the pulmonary ventilation data of Penrod[89] and of Lovelace et al.[83] Again, these estimates correlate well with more recent data from other aircraft types. In 1965, Lorentzen measured oxygen consumption in five pilots flying a jet trainer aircraft.[90] Aerobatic manoeuvres, designed to simulate supposed workloads during combat, were undertaken and a mean value of 97kcal.m^{-2}.h^{-1} obtained. This high figure, when compared with all other studies (except helicopters in low hover), was obtained from data collected over a very short time, with consequently little chance of steady state conditions being present. There were also some outward leaks from the facemask, thus shedding doubts on the accuracy of the ventilation measurements. Indeed, Lorentzen had concluded that "continuous measurement and recording would naturally provide the most certain results concerning the status at each given moment during flying."

Because of the very considerable difficulties surrounding in-flight studies of this sort, several groups of workers have assessed the energy expenditure of pilots while flying simulators. The results of one such study, by Tiller et al in 1957, provided close correlation yet again with in-flight figures published previously; and indeed subsequently.[91] They are included in Table 1.3 for comparison. It is interesting to note, however, that this simulator study showed a higher energy expenditure during combat/emergency conditions than during other phases of flight: a reversal of the pattern seen during in-flight studies.

Ground-Based Studies. As Figure 1.1 (p4) shows, the modern fast jet pilot is required to operate efficiently whilst wearing a large amount of heavy clothing and equipment. It is therefore legitimate to consider the energy expenditure of aircrew after they have donned this equipment but before and during entry to the cockpit and strapping into the seat. Three such studies were undertaken at the RAF Institute of Aviation Medicine in 1974/75. In the first, the oxygen uptake of six subjects was studied during dressing, walking and strapping into a cockpit; in each of four different clothing assemblies.[92] In the second study, measurements were made while wearing the heaviest of these assemblies and walking at two different steady paces.[93] The third involved a similar study of eight subjects wearing not only normal aircrew clothing, but also chemical defence clothing.[94] The consolidated results of these studies are presented in Table 1.4. The values for energy expenditure, again in kcal.m^{-2}.h^{-1}, have been derived from those published which were limited, in this respect, just to volumes of oxygen consumed and peak values of energy expended.

Study	Date	Ref	No of Subjects	Clothing	Bulk	Wt (kg)	* Mean energy expenditure (kcal.m^{-2}.h^{-1}) during : Resting	Dressing	Walking 2.5mph	Walking 2.7mph	Walking 3.5mph	Walking 4.0mph	Strapping -in	Recovery
Withey	1974	92	6	Control		-	52	53		135			121	53
				Jet:summer low alt		12.2	46	146		159			160	55
				Jet:summer high alt		14.3	44	154		160			148	52
				Jet:winter low alt		14.7	53	162		155			153	55
				Jet:winter high alt		16.5	52	183		173			157	56
Davison	1974	93	8	Control					134		225			
				Jet:winter high alt					192		325			
				Jet: " +AVS					182		304			
Davison	1975	94	8	Helicopter AEA					154		214			
				Helicopter AEA + CD					162		217			

* Assumes an oxygen caloric equivalent of 4.838 kcal.l^{-1} and a mean body surface area of 1.9m^{2}

Table 1.4 Summary of studies of ground-based energy expenditure of subjects wearing various aircrew equipment assemblies

The conclusions drawn from these studies included the obvious one that the heavier and more restrictive the aircrew clothing, the greater was oxygen uptake. In addition, donning clothing and strapping into the seat were particularly demanding, but walking at 3 - 4 mph (4.8 - 6.4km.h^{-1}) was the most severe condition studied. Weight of clothing per se was not considered to be a major cause of the increased demand (since an additional weight belt did not alone cause an increase), and nor was a raised body temperature. Rather, it was suggested that mechanical factors such as inflexibility and friction between clothing layers was the most likely explanation. It is interesting to note that chemical defence clothing was considered to be associated with only a "slight and unimportant" increase in energy expenditure. More recent studies, although supporting this view, have also concluded that the heat load imposed by working in such equipment is considerable.[99]

The overall impression from all of this work, meagre though it is for high performance aircraft, is that pilots expend little more energy during routine flight than they do when sitting at rest. At times of severe stress, however, as for example during emergencies, aerobatics and combat, energy requirements may rise considerably; while take-off and landing require levels somewhere in between. Sharp et al[88] concluded that the available information, in 1971, was not helpful in providing physiological advice to the designers of thermal conditioning systems. This situation still obtains today. The same authors felt that a recording system, capable of accommodation in modern cockpits with minimum interference with normal operations, was essential for the elucidation of such advice and that, once available, it would be necessary to define energy expenditure for all phases of flight during appropriate flight profiles in each type of aircraft. The present study, in part, was an attempt to fulfil this need.

Clearly, however, the effects of dressing, walking to the aircraft and strapping into the seat must also be recognised, and the ability of the cabin and any personal thermal conditioning system to cope with large heat production during these phases is therefore of great relevance. The ideal system should maintain a mean skin temperature of 33°C under all conditions.[98] Besides the metabolic heat production described and implied in the above studies, Hughes, in 1968, also included clothing, air distribution and, most significantly, solar heating as the factors influencing cooling requirements.[97] He applied all these factors in a theoretical approach to define the required mass flows and cabin air inlet temperatures for thermal comfort. Current military specifications for conditioning systems require that mean cockpit air temperature in flight should not exceed 21°C (although 30 minute periods of increase to 27°C are permitted during ground operations or some in-flight manoeuvres).[96] Of all these factors, metabolic heat production during high performance flight is the least studied yet potentially the most important. In 1977, Nunneley and James concluded that "In the future, physiological conditions - (by which they meant thermal conditions) - which are traditionally regarded as uncomfortable, but innocuous, may actually limit total system effectiveness."[95]

1.3 Respiratory Requirements for Breathing Systems

The primary purpose of an aircraft breathing system is to maintain adequate oxygenation of its user during ascent into a rarefied atmosphere while imposing the minimum of interference with normal respiratory behaviour and general efficiency. This requirement may be more simply stated as adequate composition and flow at minimum resistance.

As was established above, an oxygen system should ideally impose no resistance to breathing: in practice, however, this condition is impossible to fulfil. Much of the literature in this field has, therefore, been concerned with the definition of acceptable limits of breathing resistance. Silverman et al, in 1945, concluded that "a limit on external respiratory work appears to be the best basis for stating tolerable limits of resistance."[100] Such limits are clearly needed to minimise the degree of additional work of breathing imposed by added external resistance over long periods, and to forestall any 'downstream' embarassment of cardiovascular function. In 1960, Cooper, although principally concerned with closed circuit systems, proposed standards of resistance (and methods of assessment) in terms of total rate of respiratory work done on the apparatus.[101] He modified the recommendations of Silverman et al and raised the suggested acceptable rate of additional work from their 0.6% of total work rate to 0.74%. He further suggested that apparatus should be tested between flows of 20L.min^{-1} and 100L.min^{-1}. Other workers have proposed other limits of acceptability, expressed in different terms. For example, Bentley et al, from a study of 158 mine rescue workers during exercise, concluded that 90% of a population would experience no discomfort when breathing through apparatus with low resistance expiratory valves, if the pressure swing across the apparatus remained less than 17 cm water (1.66kPa) under steady flow conditions.[102] Four years later, the same group of workers had changed their own form of expression and declared the 90% no-discomfort limit to occur if mean inspiratory work rate did not exceed 1.37 J.L^{-1}.[103]

This lack of uniformity and consistency is not helpful, particularly when physiologists are required to advise design engineers on the essential and desirable specifications of proposed breathing systems. Thus, with regard to specifications for military systems, a different and more exact method of defining design requirements has long been adopted, based upon physiological knowledge but translated into a readily comprehensible form. The specification to which the Royal Air Force subscribes (and to which the air forces of the United States, Canada, Australia and New Zealand are also signatories), and which now forms part of an Air Standardization Agreement, lays down precise performance characteristics to be met by the whole breathing system. Acceptable levels of resistance are defined at given flows and the latter, based in large part on the studies reviewed in part 1.2.3b (p9 et seq) above, are usually derived from mean values plus twice the standard deviation, since variations between maximum and minimum values in a large group may be as much as 100%.[34] In 1965, Ernsting [34] listed the ideal requirements for an oxygen system, on this basis, thus:

- maintenance of normal alveolar oxygen tension up to 33,000 feet (10,059m).

- provision of minute volumes of up to 50L.min^{-1}.

- provision of peak flows of up to 250L.min^{-1}.

- total pressure change at the mouth during respiration of less than 2.5 cm water (0.24kPa) at peak inspiratory and expiratory flows of 50L.min^{-1}.

Royal Air Force design specifications, for many years, reflected the technical impossibility of meeting such an ideal although certain minimum requirements, including that of the ability to cope with minute volume demands of 55L, were set. No peak flow limits were defined in the early Air Standards but RAF production tests did require maximum peak flows of 110L(NTP).min^{-1} (and later 150L(NTP).min^{-1}) and minute volumes of 45L.[104] The need to revise these limits upwards was fully appreciated, and was confirmed by the in-flight study of Macmillan et al in 1976, (p9).

The extant Air Standardization Agreement (of 1982)[105] calls for whole system limits (in the absence of safety pressure) as set out in Table 1.5.

Peak Inspiratory & Expiratory Flow $L(ATPD).min^{-1}$	Mask Cavity Pressure cm water (kPa) Minimum	Maximum	Swing	Swing (peak only)
30	- 3.81 (-0.38)	+ 3.81 (+0.38)	5.08 (0.50)	4.06 (0.4)
90	- 5.59 (-0.55)	+ 6.60 (+0.65)	8.64 (0.85)	6.01 (0.6)
150	-11.43 (-1.12)	+10.16 (+1.00)	17.78 (1.75)	10.16 (1.0)
200	-19.30 (-1.90)	+15.24 (+1.50)	30.48 (3.00)	15.24 (1.5)

NB 1. The system shall be capable of meeting peak inspiratory and expiratory flows of up to $200L(ATPD).min^{-1}$ with rates of change of flow of at least $20L(ATPD).sec^{-2}$ at these peak flows.

2. The added dead-space (ie mask cavity volume) shall be less than 200ml.

3. The system shall be capable of meeting a minute volume requirement of up to $60L(ATPD).min^{-1}$.

Table 1.5 Current flow and pressure requirements for military breathing systems

In 1983, Macmillan, in a review paper[106], discussed the performance and shortcomings of oxygen systems fitted to current NATO fighter aircraft and concluded that deficiencies existed in both performance and operational effectiveness of all the major components of the systems studied. For example, the performance of some oxygen masks, when assessed alone, did not meet the minimum criteria laid down in Table 1.5 for whole systems. This is particularly disappointing since it has been known for almost 20 years that the mask hose and the mask inspiratory and expiratory valves are the main source of added respiratory resistance in military breathing systems , and clearly little has been accomplished by way of improvement since. This particular aspect will be discussed further in Part 5, but Macmillan's summary ended with the statement that "Elimination of these deficiencies should be the primary aim in the design of new systems for future combat aircraft."

1.4 Summary

The literature concerned with the study of physiological variables in flight has been reviewed, with particular reference to respiratory physiology during high performance flight. The overall impression must be one of a paucity of information in this field, largely as a consequence of technological inabilities, difficulties with instrumentation and the need for a dedicated test aircraft. Despite these drawbacks, in-flight monitoring and recording of, particularly, cardiovascular variables has been extensively and convincingly demonstrated, even in high performance vehicles. The situation with respiratory variables is less well-advanced and many pertinent questions still remain. Figure 1.3 summarises the interaction between the various facets of in-flight respiratory physiology. It was the intention of the present study to investigate some of these interactions and to try to answer some of the outstanding questions.

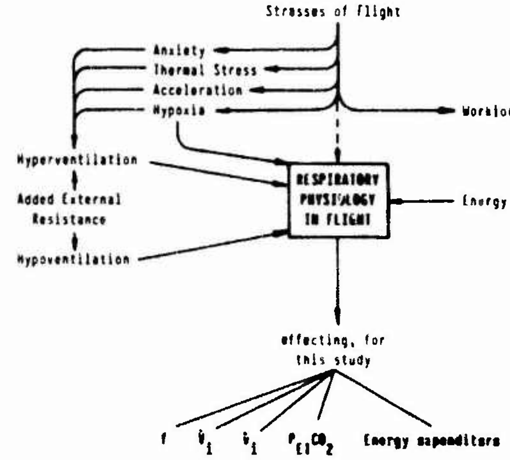


Figure 1.3 Some of the factors which may affect respiratory physiology in flight

Part 2 - THE PRESENT STUDY

2.1 Aim and Scope

The aim and scope of the present study was to measure and record basic respiratory data during high performance flight; reliably, continuously and without compromising either the operational capability of the subject pilot or his safety. This was to be achieved in a modern jet aircraft, the intention being to describe the respiratory responses to flight in as many subjects as possible using standard flight profiles to allow comparison. The respiratory variables of frequency and inspired flow (and hence inspired volume) were to be measured using a system with as little added external resistance as possible. A facility to allow measurement of the added resistance actually imposed in flight, and hence monitor the performance of the system, was to be available. Measurement of inspired gas temperature, aircraft cabin altitude (and therefore ambient pressure) and elapsed time was also necessary to allow conventional reduction and analysis of data to be carried out. Measurement and recording of the 'metabolic/respiratory' variable of breath to breath mask cavity carbon dioxide tension (and specifically of $P_{ET}CO_2$), using an on-board infra-red carbon dioxide analyser, was to supplement the basic respiratory investigation. This would provide a means whereby carbon dioxide production and, by derivation, oxygen utilization (and hence energy expenditure) could be related to various phases of flight. Furthermore, continuous measurement of $P_{ET}CO_2$ would provide a clear indication of the occurrence of hyperventilation.

As would be expected, the safety of the subject pilot was to be of paramount importance. Approval in this respect was required, sought and given at each stage of the study from the responsible medical, executive and engineering authorities.

2.2 Equipment

2.2.1 Hawker Hunter T7 Aircraft. It will be apparent from the discussions in Part 1 that a dedicated test aircraft is virtually a sine que non for in-flight physiological research; and particularly so for high performance flying. The RAF Institute of Aviation Medicine is currently unique in the western world in that it does possess a high performance aircraft. Indeed the aircraft used in this study, a Hawker Hunter T (Trainer) Mark 7, is the latest of 24 different types to be employed by the laboratory over the past 42 years.[180] The Hunter T7 (Aircraft No XL563: Figure 2.1) has been used by the Institute since 1963 but was in fact the first production version of this mark to be built, and made its maiden flight on October 11 1957.

Figure 2.1 The RAF Institute of Aviation Medicine's Hawker Hunter T Mark 7 Jet Aircraft

The possession by the Institute of this dedicated research aircraft enables it to be modified and instrumented on a permanent basis in the cause of in-flight experimentation. Thus, the recording of in-flight variables is a routine if not simple procedure; as is the installation of experimental breathing systems such as that used in this study. Furthermore, the employment of a Medical Officer Pilot as captain of the aircraft allows close scientific and medical supervision of airborne research projects.

The Hunter is a two-seat (side by side) advanced jet trainer powered by a single Rolls Royce Avon 122 engine capable of developing 8,000 pounds thrust. Although it is now over 30 years old, it is designated a high performance aircraft by virtue of its ability to fly at low level at speeds greater than 420 knot (778.25 $km.h^{-1}$) and to sustain turns of up to +6Gz. The Hunter has a low differential cabin pressurization system which maintains cabin altitude below aircraft altitude in a relationship of approximately ½ aircraft altitude + 2,000 feet (610m). So, for example, when the aircraft altitude is 30,000 feet (9,144m), the cabin altitude is 16,500 feet (5,031m). The pressurization profile may be summarised thus:

Aircraft Altitude feet (m)	Cabin Altitude feet (m)
10,000 (3,048)	8,000 (2,438)
20,000 (6,096)	13,000 (3,962)
30,000 (9,144)	16,500 (5,031)
40,000 (12,192)	22,500 (6,858)

2.2.2 Aircraft Recording System. Calibrations and in-flight variables were recorded on a 7-channel HER 400M magnetic tape recorder (Recording Designs Laboratories (EMI)) installed in the magazine bay of the aircraft. This device is designed to record data accurately under severe environmental conditions, including low barometric pressure, low temperature, vibration and sustained accelerations. The system, which conforms to Inter-Range Instrumentation Group (IRIG) standards, is capable of 65 minutes continuous FM recording of physiological and aircraft data on six channels, each with a nominal bandwidth of DC to 625 Hz at 1.875 $in.sec^{-1}$ tape speed. The seventh channel is used for a tape position index.[**] When replayed on the ground, the data are in a suitable form for either reproduction on a trace recorder or analogue reduction. Amplifiers for both record and reproduce facilities are in the form of plug-in cards which are pre-selected for the transducers to be used. There are two record amplifiers for each channel. The first is a pre-amplifier card specifically designed to condition each transducer output signal to +/-1.4V full scale, while the second is an FM record amplifier card (Pemco) which converts the pre-amplifier output signal into frequency modulated form capable of driving the record heads. The record amplifier is a voltage controlled oscillator which is deviated +/-40% by the input signal (in +/-1.4V). At 1.875 $in.sec^{-1}$, the output centre frequency is 3.375 kHz and the +40% and -40% deviation frequencies are 4.725 kHz and 2.025 kHz respectively. One FM reproduce amplifier card produces an output voltage (+/-1.4V) proportional to the incoming frequency from any one of the six data channels via head multiplexer and channel selector cards, and another decodes the index signal. Power for the system is derived from a transformer driven by the aircraft's 115V 400 Hz supply. A pilot control panel and recorder control box are mounted in the cockpit. These allow the pilot to monitor and check recorder function: a downstream monitor facility enables the pilot to select any one of the six data channels for display. An oscillator/demodulator unit in the cockpit is linked into the system when AC tranducers are being used. Finally, a ground monitor unit can be connected to aid calibration. It incorporates channel selection and display facilities, and can initiate all recorder functions.

The following were recorded in the present study :

a. Channel 1 - Tape Index (IRIG).

b. Channel 2 - Inspired Gas Temperature (recording range: 10 - 35°C), via a thermistor bead (performance range: 0 - 100°C, but reduced electrically to the required recording range) just downstream of the Fleisch flowmeter.

c. Channel 3 - Cabin Altitude (as pressure), (recording range: Ground Level - 28,000 feet (8,534m)), via a Bell and Howell absolute pressure DC transducer (performance range: 0 - 15 $lb.in^{-2}$ (0 - 103.4kPa)).

d. Channel 4 - Aircraft Acceleration, (recording range: -1 to +7 Gz), via a Statham type (A6-A-350) +/-6Gz transducer.

e. Channel 5 - Carbon Dioxide Tension, (recording range: 0 - 60 mmHg (0 - 7.99kPa)) or Mask Cavity Pressure, via an SE Labs transducer (recording and performance range: +/-10 in water (+/-2.49kPa)) or Celesco transducer (recording and performance range: +/-10 cm water (+/-0.98kPa)).

f. Channel 6 - Inspiratory Flow, (recording range: 0 - $300L.min^{-1}$), via a No 3 Fleisch flowmeter and Validyne variable reluctance pressure transducer (performance range: +/-5 cm water (+/-0.49kPa)).

2.2.3 Low Resistance Breathing System.

2.2.3a Oxygen Supply System. Modern military aircraft are routinely equipped with pressure-demand oxygen systems in which the oxygen regulator delivers the correct air-oxygen mixture to the user, on demand, to maintain alveolar oxygen tension at about 103 mmHg (13.73kPa) at all altitudes up to about 30,000 feet (9,144m). Above that altitude, 100% oxygen is delivered. Furthermore, a 2 - 4 mmHg (0.27 - 0.53kPa) overpressure (safety pressure) is automatically delivered to the system when above 12,000 - 15,000 feet (3,658 - 4,572m) to ensure that any leaks are outbound and that the respired gas is not inadvertently diluted with cabin air. Should cabin altitude exceed about 38,000 feet (11,582m), 100% oxygen is automatically and continuously delivered to the respiratory tract under positive pressure (pressure breathing), the level of pressure being related to altitude, in order to maintain adequate alveolar oxygenation. The requirements for both safety pressure and pressure breathing make the design and engineering of such systems complicated, and result ipso facto in the imposition of added external resistance. A continuous flow system, on the other hand, while not easily able to provide these features, can be engineered more simply and sources of added resistance can be minimised. The lack of control over, or knowledge of, the composition of the breathing gas is, however, a major disadvantage of such a system which must consequently provide sufficient flow to ensure an adequate supply of oxygen under all circumstances. The placement of a suitably-sized reservoir upstream of the user not only helps to prevent wastage from the continuous flow of gas but also acts as a source of additional oxygen at times of high demand.

For these experiments the standard Hunter aircraft oxygen system was not used by the subject pilot. The Low Resistance Breathing System (LRBS) supplied the port seat in place of the normal system.

The LRBS, shown schematically at Figure 2.2, consisted of a continuous flow of oxygen at $7L(NTP).min^{-1}$ from the medium pressure ($70lb.in^{-2}$ (482.6kPa)) aircraft supply to a 14.3ml capacity reservoir mounted on a removable 'shoe' positioned behind the port ejection seat. The choice of this flow and reservoir size was such as to ensure that hypoxia would not be a concern when any anticipated demand was placed on the LRBS during normal aircraft operations; it was not, however, based on any existing or planned breathing system. Flow to the subject pilot from the reservoir was measured by a Fleisch flowmeter mounted at the reservoir outlet. Delivery was then via a 4 feet (1.23m) length of 7/8 in (22.22 mm) internal diameter anti-kink hose routed on, and attached to, the left-hand side of the seat and incorporating a pull-off lanyard. Connections at both the reservoir and the mask-hose ends of the hose were by means of 7/8 in (22.22 mm) smooth-bore quick-release connectors with pull-off loads of 20 - 25 pounds-force (88.96 - 111.2 N).

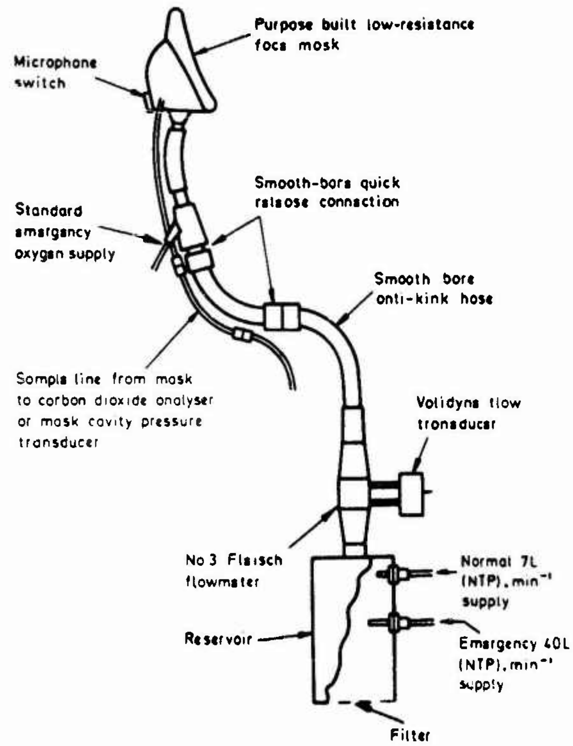


Figure 2.2 Schematic arrangement of the LRBS

A high flow of oxygen, at 40L(NTP).min^{-1} (to ensure that there would be no risk of hypoxia even at cabin altitudes of 30,000 - 35,000 feet (9,144 - 10,668m)) was available via the LRBS in the event of an oxygen system emergency. This flow was initiated by rotating a barometric by-pass valve mounted aft of the port console and its operation was signalled in the cockpit by a red indicator light mounted below the 70lb.in^{-2} magnetic indicator on the instrument panel. In addition, the flow was automatically initiated if cabin altitude exceeded 25,000 feet (7,620m). A further independent oxygen supply, from the standard Emergency Oxygen (EO) set, was available to the pilot via a special smooth-bore mask-hose connector.

It must be emphasised that the continuous-flow LRBS did not provide safety pressure or pressure breathing facilities and that, for safety reasons, a good mask fit was essential; this was also true for the success of the study. The aircraft was limited to a maximum aircraft altitude of 35,000 feet (10,668m) when the LRBS was in use.

2.2.3b Oxygen Mask Assembly. A conventional RAF Type P1/Q1 oxygen mask is routinely used during Hunter flying. A P1/Q1 mask consists of a flexible facepiece supported by a rigid exoskeleton. The facepiece incorporates a non-return inspiratory valve and a split compensated non-return expiratory valve. An anti-suffocation device is also fitted in the form of a special connector at the end of the mask hose. These valves, and the special connector, impose considerable resistance to both expiration and inspiration.

For the LRBS, a modified, low resistance, Type P/Q (medical, ie non-dermatitic) series mask was provided for the subject pilots. The valve arrangement in this modified mask is shown diagramatically at Figure 2.3a and is compared with the standard arrangement at Figure 2.3b.

The experimental mask assembly consisted of a wide-bore corrugated rubber mask hose connected to the conventional expiratory port of the faceplece but providing the inspiratory pathway. A non-return inspiratory valve was located in this port and the mask compensation pipe was blanked off. Expiration, to the cabin atmosphere, was via the conventional inspiratory port and a second port bored in the left cheek of the mask. Modified non-return step valves were mounted in both sites. A mask tapping was mounted in the right-hand side of the mask and provided the sampling port for either P[illegible] measurement or mask cavity pressure measurement. From this tapping, a flexible sampling tube of 1/8 in ([illegible] mm) internal diameter was routed, to either the CO_2 analyser or the mask cavity pressure transducer, via a seat pull-off connector and secured at 6 in (15.24 cm) intervals alongside the oxygen supply hose. The connector for this sample tube had a pull-off load of approximately 5 pounds-force (22.24 N). The smooth-bore, mask hose, quick-release connector incorporated a conventional attachment for the emergency oxygen supply.

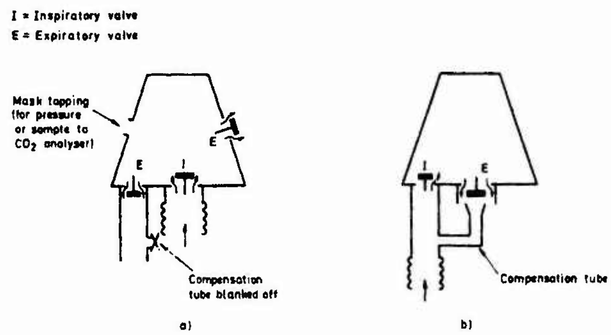


Figure 2.3 Valve arrangement of oxygen masks
a. Low resistance mask b. Standard P1/Q1 mask

2.2.4 Carbon Dioxide Analyser. Breath to breath PCO_2 was measured by an on-board infra-red gas analyser (Leybold-Heraeus GmBH). This industrial machine was modified and tested for aircraft use prior to this study. Laboratory assessment, both at ground level and at simulated altitudes in a decompression chamber, had shown its performance to equal that of a mass spectrometer[110] and these studies will be described further in Part 3. The machine was also shown to be stable under high levels of positive Gz acceleration and during vibration.

The analyser, shown diagramatically at Figure 2.4, works on the non-dispersive principle, the infra-red radiation being produced from a single source before being divided into two beams of equal intensity. A chopper, driven by eddy currents at a frequency of 250 Hz, allows the beams to pass alternately through a cell with reference and sample sides and then into a radiation receiver consisting of linked absorption and compensation chambers. The receiver is sensitised to the component of interest, in this case by filling it with carbon dioxide, and the absorption chamber is exposed to the beams of infra-red radiation. When the infra-red intensity of the sample beam absorbed by the receiver changes in response to an alteration in the concentration of carbon dioxide, a temperature, and thus a pressure, fluctuation occurs resulting in a flow of gas between the absorption and compensation chambers. A micro-flow sensing device - which consists of a constant temperature micro-anemometer of micron dimensions[111] (hence its insensitivity to accelerations) - converts this compensation flow to an electrical signal, which is then amplified and demodulated to give a DC output signal proportional to concentration. If carbon dioxide is not present, the effect of the two beams in the receiver is identical and no compensation flow occurs.

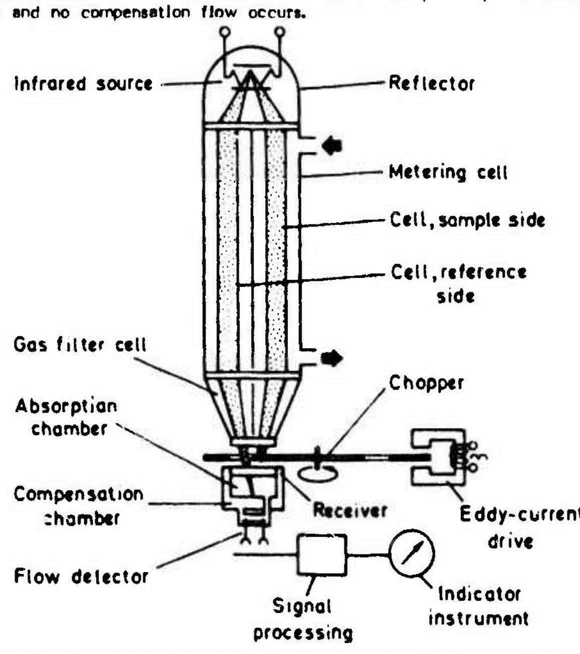


Figure 2.4 Principle of operation of the carbon dioxide analyser

For use in flight, the analyser was re-housed as two units. The sensor itself and its sample pump were mounted in a small box secured to the cockpit rear bulkhead behind the port ejection seat. A control box was installed in place of the starboard gunsight on the right of the pilot's instrument panel. The box had a system On/Off switch positioned halfway down its right-hand side; power On being selected when the switch was up and confirmed by a red light-emitting diode above the switch. The unit required no more than 45 sec to become stable after switching on and a green ready light, below the switch, illuminated after this period. The system was then sampling, the pump being functional as soon as power was applied to the airborne tape recorder.

2.2.5 In-flight Carbon Dioxide Calibration Unit. In-flight calibration of the carbon dioxide analyser was accomplished by sampling cabin air and two calibration gases, in sequence, via a unit mounted with the LRBS on its 'shoe'. The in-flight calibration system is shown schematically at Figure 2.5. The calibration gases were contained in two 70L(NTP) gas cylinders from which samples were drawn into the analyser via a small plenum chamber vented to ambient to reduce the gas pressure. The cabin air sample was also drawn in via the plenum. Flows were governed by three 30 $lb.in^{-2}$ (206.8kPa) pinch solenoids (Brunswick/Technetics) mounted close to the plenum. Figure 2.6 is an exploded view of the calibration unit mounted on the LRBS 'shoe'. Controls for the airborne calibration of the CO_2 analyser were mounted on the CO_2 control box. A Cal Gas Operate locking toggle switch was located on the lower right-hand side of the box. On was selected when the switch was up and confirmed by a blue warning light beside the switch. Movement of this switch to the On position closed the mask sampling line and and opened the CO_2 analyser to the calibration gas plenum chamber. A 3-way Cal Gas Select switch was mounted on the top right-hand side of the control box and annotated A, B and C. Operation of this switch in sequence (p25) allowed sampling, first of cabin air and then of the two prepared calibration gases.

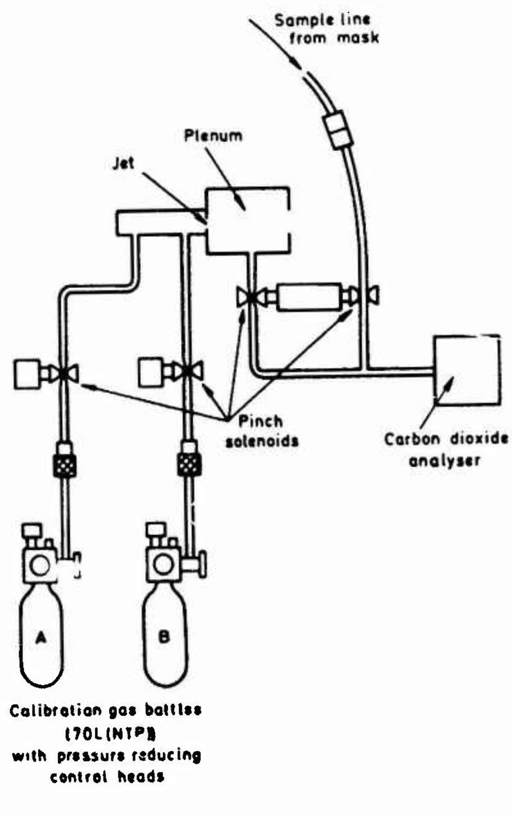


Figure 2.5 Schematic arrangement of in-flight carbon dioxide calibration unit

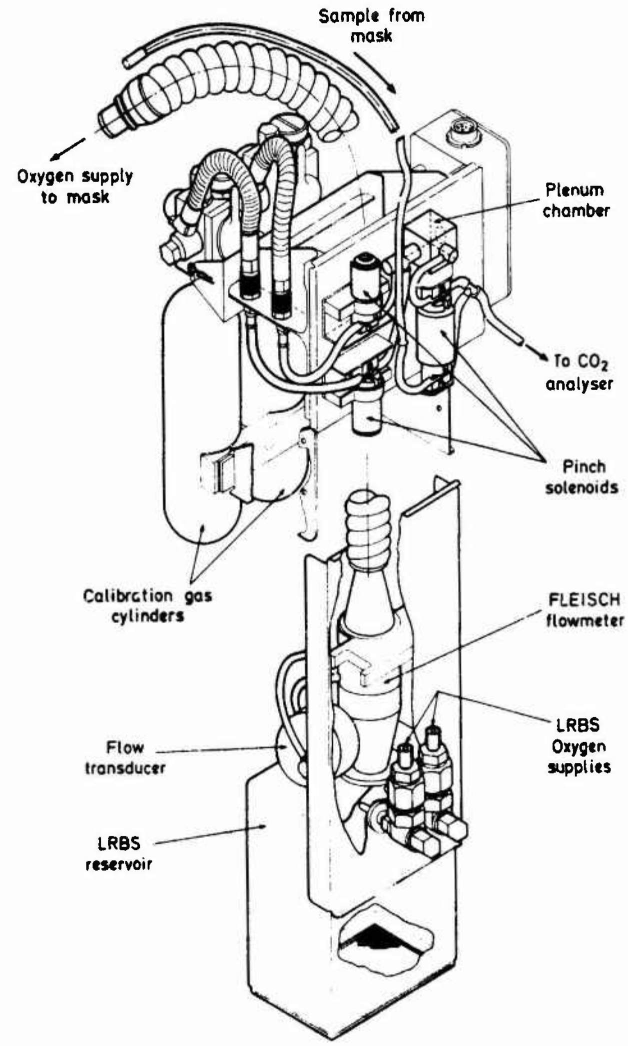


Figure 2.6 Exploded view of the in-flight carbon dioxide calibration unit mounted on the LRBS 'shoe'

2.2.6 External Requirements. In addition to the aircraft and aircraft-mounted equipment described above, certain other items were required for each experiment in this study. Thus, **ground power**, both pre-flight and post-flight, was required for calibration. Indeed, power to the recording system had to be maintained continuously throughout each mission from pre- to post-flight calibration. The transition from external to internal (aircraft-generated) power, and vice versa, required the full co-operation of ground staff and pilots to ensure that no interruption in the electrical supply to the recording system occurred. A **ground calibration facility** was required, with which to carry out and document pressure, flow, volume and temperature calibrations. During the first phase, the materials needed - calibration gas cylinders, rotameters, manometers, altimeters etc, industrial vacuum cleaner, hand pumps, oscilloscope and ground monitor unit - were housed in a purpose-built trolley. During the second phase, a military vehicle was used and was considered particularly suitable. Details of the calibration procedures are discussed below (p25 et seq). Ground level and airborne **calibration gases** for the CO_2 analyser were prepared as required and definitive analysis of these gases was carried out using the standard Lloyd-Haldane technique.[113]

Finally, a general arrangement and recording schematic is shown at Figure 2.7, while Figure 2.8 shows a general view of the aircraft experimental installation.

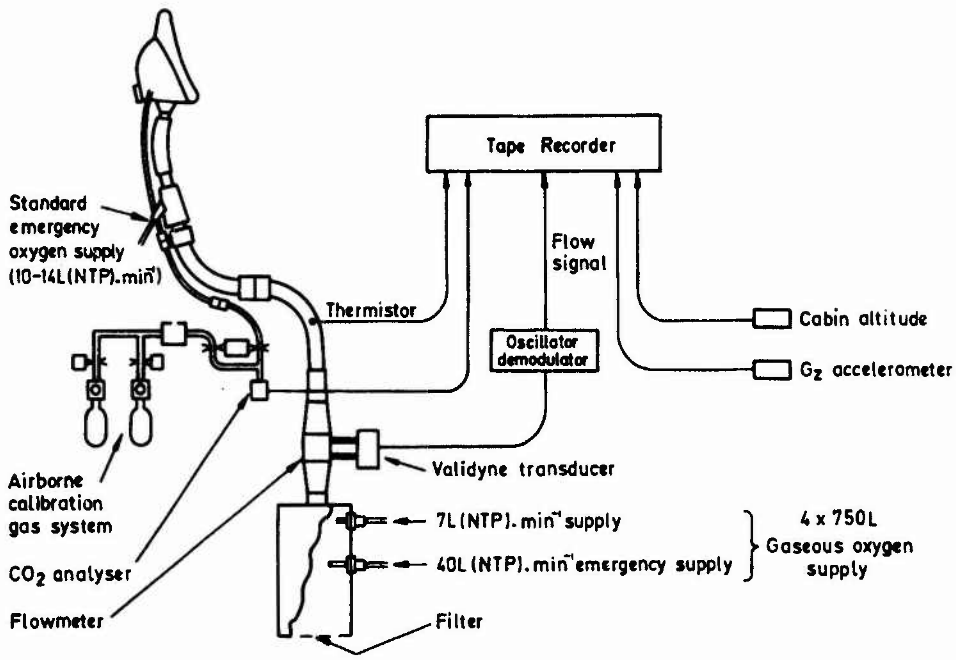


Figure 2.7 General arrangement and recording schematic

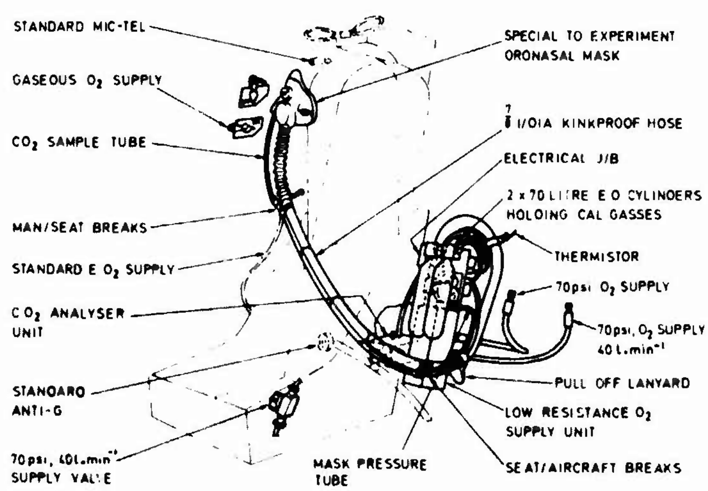


Figure 2.8 Aircraft experimental installation

2.3 Subjects

Eighteen healthy male subjects, with a mean age of 36.3y (range 26 - 55), each flew up to four experimental flights. All eighteen were experienced RAF General Duties pilots: twelve were Hunter squadron pilots based at RAF Brawdy in South Wales, and six were test pilots employed at the Royal Aircraft Establishment, Farnborough. All were thoroughly familiar with the Hunter aircraft.

Table 2.1 lists the personal details of the subjects together with derived values for body surface area, standard basal metabolic rate and respiratory dead-space. The last was derived by several methods, as shown in the footnotes to the table. The value derived by the method of Cotes[113] (age in years + weight in pounds) was used in Part 4 of this study, and the others are included in the table for comparison and interest.

Subject	Age	Ht	Wt		Surface Area *	Standard BMR **	Dead-Space (V_{Ds}) (ml) ***			
	(y)	(cm)	(kg)	(lb)	(m^2)	($kcal.m^{-2}.h^{-1}$)	a	b	c	d
PJ	31	183	86	190	2.08	39.5	190	221	173	184
SW	27	187	80	176	2.05	39.5	176	203	183	173
KB	39	175	70	154	1.85	39.5	154	193	155	156
DM	33	181	82	181	2.03	39.5	181	214	167	177
AS	31	176	68	150	1.83	39.5	150	181	157	152
FS	28	174	65	143	1.78	39.5	143	171	153	147
MA	26	177	72	159	1.89	39.5	159	185	159	159
DH	36	173	80	176	1.94	39.5	176	212	151	173
JF	40	180	68	150	1.86	38.5	150	190	166	152
LB	55	173	73	161	1.86	37.5	161	216	151	161
RB	27	174	75	165	1.89	39.5	165	192	153	164
DF	28	181	80	176	2.00	39.5	176	204	167	173
MB	36	180	72	159	1.91	39.5	159	195	166	159
HM	52	175	91	201	2.07	37.5	201	253	155	193
GW	45	160	74	163	1.93	37.5	163	208	166	163
RR	38	185	94	207	2.18	37.5	207	245	178	198
AA	39	174	64	141	1.77	37.5	141	180	153	145
JA	43	183	88	194	2.11	38.5	194	237	173	187
Mean (n = 18)	36.3	178	77		1.95	38.8				
Ref 89 [1942] (n = 8)	25.8	176	68		1.79					
Ref 83 [1970] (n = 22)	37	179	79		1.97					

Notes * Surface Area $Wt^{0.425} \times Ht^{0.725} \times 71.84$ Ref 114

** Standard BMR, derived from surface area by method of Dubois and Aub. Thus, for males,

age 20 - 40, BMR = 39.5 $kcal.m^{-2}.h^{-1}$
age 40 - 50, BMR = 38.5 "
age 50 - 60, BMR = 37.5 " Ref 115

*** Dead-Space:

a - V_{Ds} = Wt in pounds Ref 116
b - V_{Ds} = Wt in pounds + Age in years Ref 113
c - $V_{Ds} = 3.846 \times Ht(cm)^{2.499} \times 10^{-4}$ Ref 117
d - $V_{Ds} = 1.765 \times Wt(kg) + 32.16$ Ref 117

Table 2.1 Personal details of subjects, including derived variables

2.4 Methods and Operational Details

2.4.1 Laboratory Assessments. Laboratory assessments were carried out on the LRBS with the intention of not only measuring its effectiveness and resistance but also its ability to satisfy the requirements for safe in-flight use.

The behaviour of the LRBS delivery system and mask assembly was studied under steady-state and dynamic flow conditions. The results of these tests are given in Part 3 (p28 et seq), together with a comparison of the LRBS performance and that of current in-service breathing systems.

Satisfactory equipment integration checks completed the pre-flight clearance studies. As with any new or altered items of equipment, it was necessary to ensure that no conflict with existing cockpit facilities would occur, such as snagging by hoses, and that the assembly would be comfortable to use. These aspects were confirmed by assessing a subject pilot in a Hunter mock-up cockpit. It was also necessary to confirm that escape from the aircraft during a ground emergency would be unhindered by the experimental equipment and this too was confirmed by undertaking emergency egress drills in the cockpit. A subject was then suspended in an ejection seat, to which the appropriate components of the LRBS had been fitted, in order to establish that man-seat separation, during an ejection sequence, would be clean and unrestricted by the new equipment; hence the need for defined pull-off loads at the hose and sample line connections.

Finally, a Trial Installation, during which the entire experimental system was formally assessed for compatibility and safety in the aircraft cockpit, preceded the flight programme.

2.4.2 Operational Details.

2.4.2a General. In accordance with standard RAF IAM practice, a formal flight trial protocol was written for approval by the medical, engineering and executive (flying) authorities responsible for flight research. This protocol described the aim of the trial, the equipment to be used and the flight profiles to be adopted. An important safety aspect of the protocol was the inclusion of a separate Pilot Briefing Sheet which briefly duplicated the salient features of the protocol itself but also gave specific details of the procedures to be adopted in the event of an in-flight emergency.

The flight trial was conducted in two phases. The preliminary phase was conducted at the Royal Aircraft Establishment, Farnborough, and involved test pilots as subjects, (RAE phase). Measurement of mask cavity pressure was carried out during these flights. This phase was then followed by a longer, more extensive trial at RAF Brawdy, using squadron pilots from a Tactical Weapons Unit, (TWU phase). Carbon dioxide analysis was substituted for mask cavity pressure measurement for this phase. Results from each experimental sortie (flight) provided the basis of any changes needed in the flight plan of the subsequent sortie.

The LRBS was a relatively simple system and raised no new problems as far as recording in flight was concerned. On the other hand, the carbon dioxide analyser embodied new concepts and was technically very sophisticated. In addition, the requirement for in-flight calibration was especially challenging. Therefore, throughout the second phase of the study, it was intended that, should problems arise with the carbon dioxide analyser, the flights would continue using the LRBS alone and re-substituting mask cavity pressure measurement for carbon dioxide analysis.

2.4.2b Ground Calibration. Calibration was carried out pre-flight and post-flight, with continuous electrical power, as follows:

i. Channel 2. The physical relationship between resistance and temperature was exploited to calibrate the temperature channel. A decade resistance box was used calibrate the thermistor bead, over the range 10 - 35°C in 5°C increments.

ii. Channel 3. The cabin altitude transducer was calibrated against an aircraft altimeter (which was itself regularly checked for linearity against a mercury barometer), using a hand vacuum pump, at ground level, 14,000 feet (4,267m), 21,000 feet (6,401m), 28,000 feet (8,534m), 7,000 feet (2,134m) and ground level, in that order. The airfield barometric pressure was noted for each flight.

iii. Channel 4. The aircraft accelerometer was calibrated at 0, -1 and +1 Gz by releasing its retaining clamp and rotating through 180° in 90° increments. The linearity of this transducer over its whole range was confirmed regularly by using a centrifuge.

iv. Channel 5. For carbon dioxide measurement, calibration gases were supplied as follows:

A - nominal 2.5% CO_2 in air
B - nominal 5.0% CO_2 in air
C - nominal 7.5% CO_2 in air
D - nominal 10.0% CO_2 in air

The analyser was calibrated with these gases, via a reducing valve and the sampling line, in the order: air, B, C, D, A and air.

When mask cavity pressure was to be recorded, the transducer was calibrated, using a water manometer or a micromanometer (Air Resources Ltd, MP20A) and sylphon bellows, initially at 0, +1, +2, +3, +4 and +5, followed by 0, -1, -2, -3, -4 and -5 in water, but later at the same values in cm water.

v. Channel 6. The inspiratory flow channel was calibrated with the LRBS supply on, using a rotameter connected to a vacuum source which drew gas through the Fleisch flowmeter, at 0, 120, 180, 240, 300, 60 and 0L.min^{-1}, in that order. This was followed by drawing four x 5L volumes through the system using a 5L hand pump, to calibrate subsequent electrical integration of the flow signal.

2.4.2c Airborne Calibration. Airborne calibration of the carbon dioxide analyser was carried out by the Captain of the aircraft, who occupied the right-hand seat. Calibration was specifically required at those times designated by the flight profiles, although this generally occurred whenever the need to stabilize at a new flight level was called for. The switching sequence, which took 60 - 90 seconds with at least 10 seconds in each position to ensure a stable measurement, was as follows:

Cal Gas Operate switch On
Cal Gas Select to A (sampled cabin air)
Cal Gas Select to B (sampled mid-range CO_2)
Cal Gas Select to C (sampled top range CO_2)
Cal Gas Select to B
Cal Gas Select to A
Cal Gas Operate switch to Off

2.4.2d Flight Profiles. Four different flight profiles were chosen and followed as accurately as possible in order to allow comparison between subjects. Three of these profiles (two general handling and one combat) were highly structured and precise, while the fourth was a less structured but high workload profile. All the manoeuvres required were representative of typical elementary and advanced fighter training tasks.

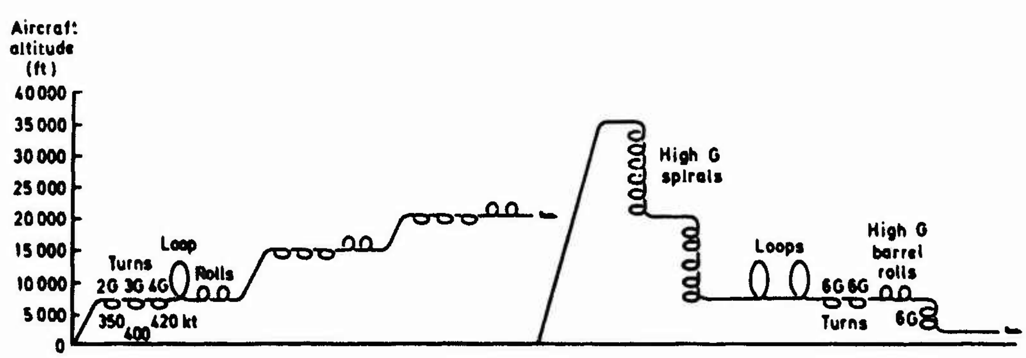
All Sorties. For all flights, the magnetic tape recorder was switched on using external power and changing tape index numbers were confirmed. Pre-flight calibration was then carried out. The subject pilot confirmed that both the normal; and emergency oxygen supplies to the LRBS were functioning correctly prior to strapping-in. Once strapped-in, he then established that the seat-aircraft connections were made. The carbon dioxide control unit was turned on, and the aircraft internal power supply was switched on, at the beginning of the pre-start checks. After landing, calibration was carried out using external power.

General Handling Sortie Type 1 (GH1). After take-off and transit to the operating area, straight and level flight was established at FL70 (7,000ft; 2,134m) for 1 - 2 minutes while the carbon dioxide analyser was calibrated. A +2Gz level turn at 350 knot (648.55km.h^{-1}) for a minimum of one minute was followed by acceleration to 400 knot (741.2km.h^{-1}) and a +3Gz level turn, again for one minute. A +4Gz level turn at 420 knot (778.25km.h^{-1}) was then carried out before re-establishing straight and level flight at FL70 (7,000ft; 2,134m) and re-calibrating the analyser. A loop was then initiated followed by one fast and one slow roll. The entire sequence was repeated, with the exception of the loop and if time and fuel permitted, at FL150 (15,000ft; 4,572m) and FL200 (20,000ft; 6,096m), with analyser calibrations at each level. The sortie finished with a period of straight and level flight, at any level, before descent procedures were started. The format of this type of sortie is shown diagramatically in Figure 2.9a.

General Handling Sortie Type 2 (GH2). After take-off and transit to the low flying area and calibration of the carbon dioxide analyser, ten minutes of general handling at low level was carried out before a climb to medium level (FL150 (15,000ft; 4,572m)) and re-calibration of the analyser. Academic steep turns, maximum rate level turns and maximum rate wind-up turns were then carried out, followed by five minutes aerobatic manoeuvring. The analyser was re-calibrated before the recovery, which included a simulated emergency, a practice forced landing and circuits to intensify the pilot's workload.

Simulated Combat Manoeuvres Sortie (SCM). After take-off and transit to the operating area, the carbon dioxide analyser was calibrated at FL350 (35,000ft; 10,668m) before a +6Gz wind-up turn descending to FL200 (20,000ft; 6,096m) was initiated. Following stabilization and re-calibration at this level, a further maximum rate spiral descent at high +Gz to FL70 (7,000ft; 2,134m) was carried out. After re-calibration, the sortie concluded with a series of two loops, two +6Gz turns, two high +Gz barrel rolls and a +6Gz descending turn to 2,000 feet AGL (610m) before a final calibration and recovery to base in straight and level flight. The format of this type of sortie is shown diagramatically in Figure 2.9b.

1 vs 1 Air Combat Manoeuvres Sortie (ACM). A standard Tactical Weapons Unit (TWU) Air Combat Manoeuvre 1 vs 1 sortie was flown on an availability basis, when the research aircraft was one of the pair. Alternatively, the IAM Hunter acted as the attacking aircraft for a TWU bounced Simulated Attack Profile (SAP) or low level ACM sortie. The carbon dioxide analyser was calibrated on several appropriate occasions during such sorties.



a. General Handling Sortie Type 1   b. Simulated Combat Manoeuvres Sortie

Figure 2.9

2.4.2e In-Flight Procedures. With the exception of the modified mask assembly, the subject pilots wore normal Hunter Aircrew Equipment Assemblies (AEA), including anti-g trousers. Each subject pilot was issued with a Pilot Briefing Sheet, as described above, which included the in-flight emergency procedures. A copy of this Briefing Sheet is shown at Appendix A, (pA1).

The second pilot, the aircraft Captain, also acted as safety pilot and observer. He was responsible for the completion of the flight profile log, by noting the tape index numbers at the following events:

a. Start of take-off roll.
b. Entry to straight and level flight.
c. Entry to +2, +3, +4 and +6Gz turns.
d. Entry to loops, rolls and spirals.
e. Change of flight level and start of next procedure.
f. Carbon dioxide calibration during flight.
g. Any period of deviation from the profile sequence.

An example of a typical log is shown at Appendix B, (pA3).

2.4.3 Measurement of Control Values. Control values for respiratory frequency, inspiratory minute volume, inspiratory peak flow and end-tidal carbon dioxide tensions were obtained after the flight trials. The LRBS and carbon dioxide analyser were removed from the aircraft and the system was re-mounted on a purpose-built trolley. After calibration of the equipment, the subjects were assessed sitting at rest for five minutes wearing normal clothes (with the exception of the experimental mask and a lightweight supporting helmet). The required variables were recorded on a pen recorder (Watanabe 8-channel Linearcorder Mk VII) for later analysis. The control values are reported in the appropriate sections of Part 4.

Part 3 - EVALUATION OF EQUIPMENT AND METHODS OF ANALYSIS

3.1 Laboratory Assessments

3.1.1 Low Resistance Breathing System. The philosophy underlying the design of the breathing system used in this study was to approach normal un-impeded respiratory behaviour as closely as possible, by lowering the degree of added external resistance, whilst retaining the safety aspects required of military equipment. It was never the intention to suggest that the low resistance system be adopted for routine service use; indeed, as described in Part 2 (p19), the LRBS was not capable of meeting some of the necessary requirements of an operational military oxygen system. Design of the system therefore principally involved reduction in the sources of resistance wherever possible. Thus, a means of continuous flow delivery, via wide-bore smooth-walled tubing and connectors, was devised; but most reduction was achieved in the design of the oro-nasal mask. Many alternative valve configurations were assessed, under both steady-state and dynamic flow conditions, before the final version was determined with valves located and orientated as described and illustrated in Part 2 (p19 and Figure 2.4a (p20)).

Steady-state mask cavity pressure changes, both inspiratory and expiratory, were measured by imposing gas flows in the appropriate direction, via a rotameter, through a backing plate on which the mask was mounted. Pressures were measured using an alcohol manometer, the results here being converted to cm water for ease of comparability. Under such steady-state conditions, at flows of 250L(NTP).min^{-1}, the mask cavity pressure levels were +2.67 to -5.46 cm water (+0.26 to -0.53 kPa). Figure 3.1 illustrates the results of the steady-state assessment of the experimental mask and compares its performance with that of RAF P/Q type masks and American MBU 5/P and A13A masks assessed in a similar manner in 1965.[107] RAF production test limits are also included, as are some results from a further (1971) study of RAF P/Q type masks.[118]

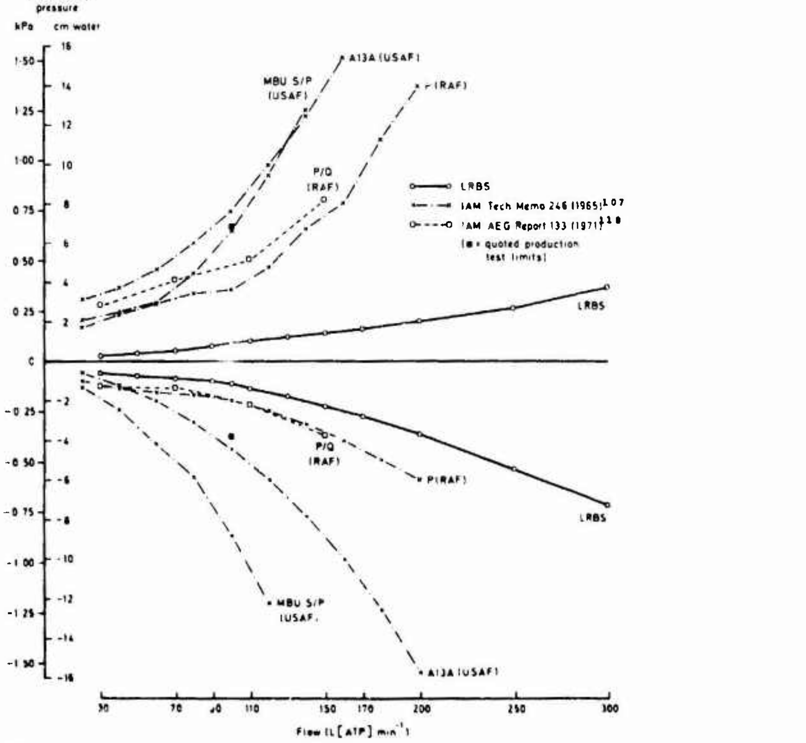


Figure 3.1 Comparison between the resistance characteristics of the LRBS mask and those of standard RAF and USAF oxygen masks, under steady-state flow conditions

Figure 3.2 illustrates the results of a steady-state assessment of the LRBS on a component basis, and compares the system with the standards for performance defined by the 1982 Air Standardization Agreement [105] (Table 1.5, p16). For the entire system, the mask cavity pressure levels, at steady flows of 250L(NTP).min^{-1}, were +2.67 to -8.51 cm water (+0.26 to -0.83kPa) with most resistance residing in the mask inspiratory valve; the rest of the system contributed little additional load.

Furthermore, mask cavity pressure swings only slightly greater than steady state figures were recorded when the LRBS was subjected to dynamic breathing levels, using a Beaver breathing simulator, representative of sedentary, light and medium exercise (pulmonary ventilations of ~8.0, 20.0 and 29.0 L.min^{-1} respectively, as defined by Silverman[108]). Figure 3.3 illustrates the results of this dynamic assessment of the LRBS, and compares them with the performance of typical current RAF and USAF oxygen systems assessed similarly.[118]

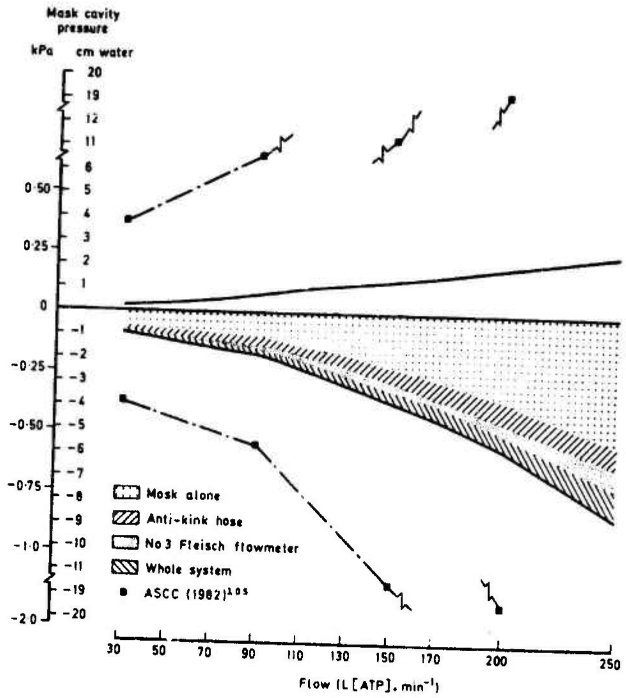


Figure 3.2 LRBS steady-state flow characteristics: component contributions to total resistance
(ASCC design standard figures are shown for comparison)

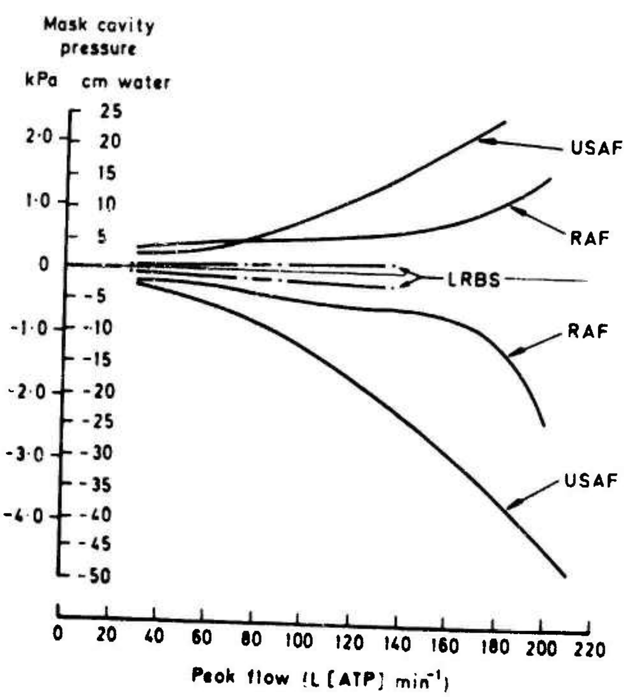


Figure 3.3 Comparison between the resistance characteristics of the and those of typical RAF and USAF oxygen systems, under dynamic flow conditions

Clearly, under both steady-state and dynamic flow conditions, the LRBS was a considerable improvement, in terms of resistance characteristics, on both the 1982 design standard[105] and current RAF and USAF oxygen systems. It was concluded that the LRBS would indeed allow a physiologically more realistic approach to the study of respiratory behaviour in flight. It would also allow a comparison to be made with the studies by Silverman et al [44,100] of the effects of added external resistance on peak flows.

Human subjects were also studied, when exercising on a cycle ergometer and during speech, at ground level and at various simulated altitudes (up to 25,000 feet (7,620m)) in a hypobaric chamber. Mask cavity pressure was recorded as were mask cavity oxygen and carbon dioxide tensions. The experiments confirmed that the system was of low resistance but, more importantly, also showed that the partial pressure of oxygen delivered to the subject would remain satisfactory under such conditions. The results of this assessment are summarised at Table 3.1. At no time, even when exercising at 100 watt and speaking, did P_IO_2 fall below 140 mmHg (18.66kPa). Rapid decompressions from 14,000 to 30,000 feet (4,267 to 9,144m), during which the emergency flow of 40L(NTP).min^{-1} was initiated, demonstrated that there would be no risk of hypoxia should decompression occur in flight: P_IO_2 did not fall below 85 mmHg (11.3kPa)

Activity	Ground Level P_IO_2 (mmHg)	Ground Level $\%O_2$	18000 feet P_IO_2 (mmHg)	18000 feet $\% O_2$	25000 feet P_IO_2 (mmHg)	25000 feet $\% O_2$
Rest	190	25	247	65	211	75
Rest + Speech	182	24	247	65	197	70
LRBS on from this point						
50 W	304	40	209	55	161	57
50 W + Speech			190	50	155	55
100 W	274	36	171	45	141	50
100 W + Speech	281	37	152	40	141	50

Table 3.1 Oxygen delivery characteristics of the LRBS to human subjects while at simulated altitudes and at several levels of activity

A cold performance test, in which the LRBS mask assembly was exposed to -40°C in a 15 knot (27.8km.h) wind for 15 minutes, confirmed that the mask valves would continue to function adequately should these extreme conditions be met after an ejection or loss of canopy.

Finally, the measurement of inspiratory flow throughout the study was accomplished by means of a Number 3 Fleisch pneumotachograph and a Validyne pressure transducer. The flowmeter, with transducer, was found to be linear over the range 0 - 300L(NTP).min^{-1} (correlation coefficient = 0.9972).

A Fleisch pneumotachograph consists of a rigid tube containing a low resistance element made up of many parallel small-bore tubes which also serve to maintain laminar flow. Provided laminar flow exists, Poiseuille's law states that volume flow of gas through the tube is directly proportional to the pressure drop along it, and independent of absolute pressure. The law may be expressed as in equation [1].

$$\Delta P = \frac{8\ell}{\pi r^4} . \dot{V} . \eta \qquad [1]$$

Where: ΔP = pressure drop along tube, ℓ = length, r = radius, $\dot{V}$ = volume flow, η = viscosity.

Since the first term will be constant for a given Fleisch instrument, only factors affecting the last two terms, viscosity and volume flow, may cause problems of measurement. Viscosity is dependent on gas composition and temperature. In the present study, the effects of the former were minimised by calibrating the Fleisch pneumotachograph with the gas which was flowing to the LRBS, so emulating the in-flight situation. Furthermore, changes in viscosity of breathing gases with altitude are extremely small. With regard to effects of altitude on measurement of volume flow, it follows from equation [1] that a given pressure drop is a measure of a specific volume flow, not mass flow. Thus, when a pneumotachograph is used at altitude, the device measures volume flow at ambient pressure and temperature; this measurement must be corrected to standard conditions (BTPS or STPD) to establish mass flow. To this end, temperature and pressure were monitored throughout these experiments and correction factors applied therefrom during analysis. So, with the support of other recorded variables, the Fleisch pneumotachograph may be considered suitable for use at altitude.

3.1.2 Carbon Dioxide Analyser. The laboratory performance of the carbon dioxide analyser had been assessed previously by Hay.[114] When in its aircraft orientation, the device was stable (with no appreciable increase in output noise and no effect on baseline) when subjected to positive accelerations of up to 8Gz, and when vibrated vertically at +/- 1Gz over the frequency range 0.5 - 20 Hz. Furthermore, in a comparative study of five subjects under four workloads at both ground level and at 25,000 feet (7,620m), the results from the carbon dioxide analyser differed from those from a Centronics MGA007 mass spectrometer by <1 mmHg (0.13kPa) over the 25 - 65 mmHg (3.3 - 8.1kPa) range of PCO_2 tensions observed. The differences were greatest at workloads >50 watt at both altitudes.

Sample flow from the mask was 1L(ATP).min^{-1} and the sample line length was 141 cm. At ground level, transit time of a marker gas from the mask cavity to the analyser averaged 0.52 sec while the 0 - 90% rise time of the device was 0.22 sec. At 25,000 feet (7,620m) the sample flow from the mask was 0.75L(ATP).min^{-1}, and the transit and 0 - 90% rise times of the analyser were 0.55 sec and 0.19 sec respectively. The small difference between the figures for ground level and 25,000 feet (7,620m) was due to the slightly diminished performance of the analyser pump at altitude; although the analyser's behaviour remained comparable to that of the mass spectrometer. A copy of the records for the analyser transit and rise times is at Figure 3.4.

The stability and accuracy of the analyser under these extreme environmental conditions, combined with its rapid response time, confirmed its suitability for in-flight use.

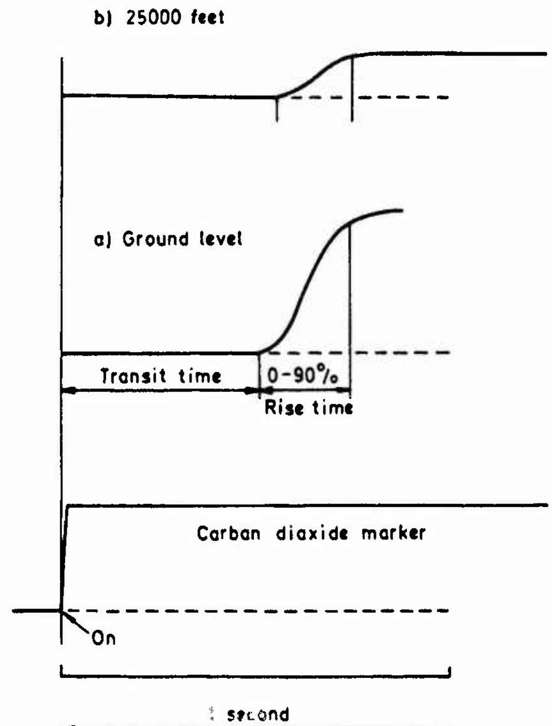


Figure 3.4 Record of carbon dioxide analyser transit and rise times at (a) ground level and (b) 25,000 feet (traced from original)

3.2 In-Flight Variables

3.2.1 General. The magnetic tape from each experimental flight was replayed at high speed immediately after landing to ensure that any instrumentation fault could be corrected before the succeeding sortie. A high fidelity record was then produced from which data were extracted. An example of such a record, including an in-flight calibration of the carbon dioxide analyser, is reproduced at Figure 3.5. Replay was accomplished by means of a Sabre III 14-channel FM IRIG intermediate band magnetic tape recorder/reproducer and the permanent record produced by either a Devices 8-channel pen recorder (RAE phase) or a Watanabe 8-channel Linearcorder Mark VII (TWU phase). The inspiratory flow signal was integrated electronically at this stage to produce inspiratory volume.

The first flight phase involved measurement of inspiratory flow and mask cavity pressure. Of the 34 LRBS flights comprising the second phase, 23 were accomplished with in-flight carbon dioxide analysis. Technical problems (power surging) with the analyser control unit meant that the remaining 11 flights were undertaken with mask cavity pressure recording instead. The pressure records were incomplete during six of these sorties because of an intermittent channel drop-out which developed just after take-off on each occasion. The problem was eventually traced to a faulty recorder card which was replaced, and the records were complete thereafter.

Calibration signals were input to the airborne recorder such that the maximum signal was at 80% of full-scale deflection, to ensure not only that physiological signals outside the calibration range would be embraced but also that any baseline drift would be accommodated. Baseline drift did not occur except for single brief periods in the carbon dioxide record of three sorties (40,41,42): the original baseline being regained within five minutes.

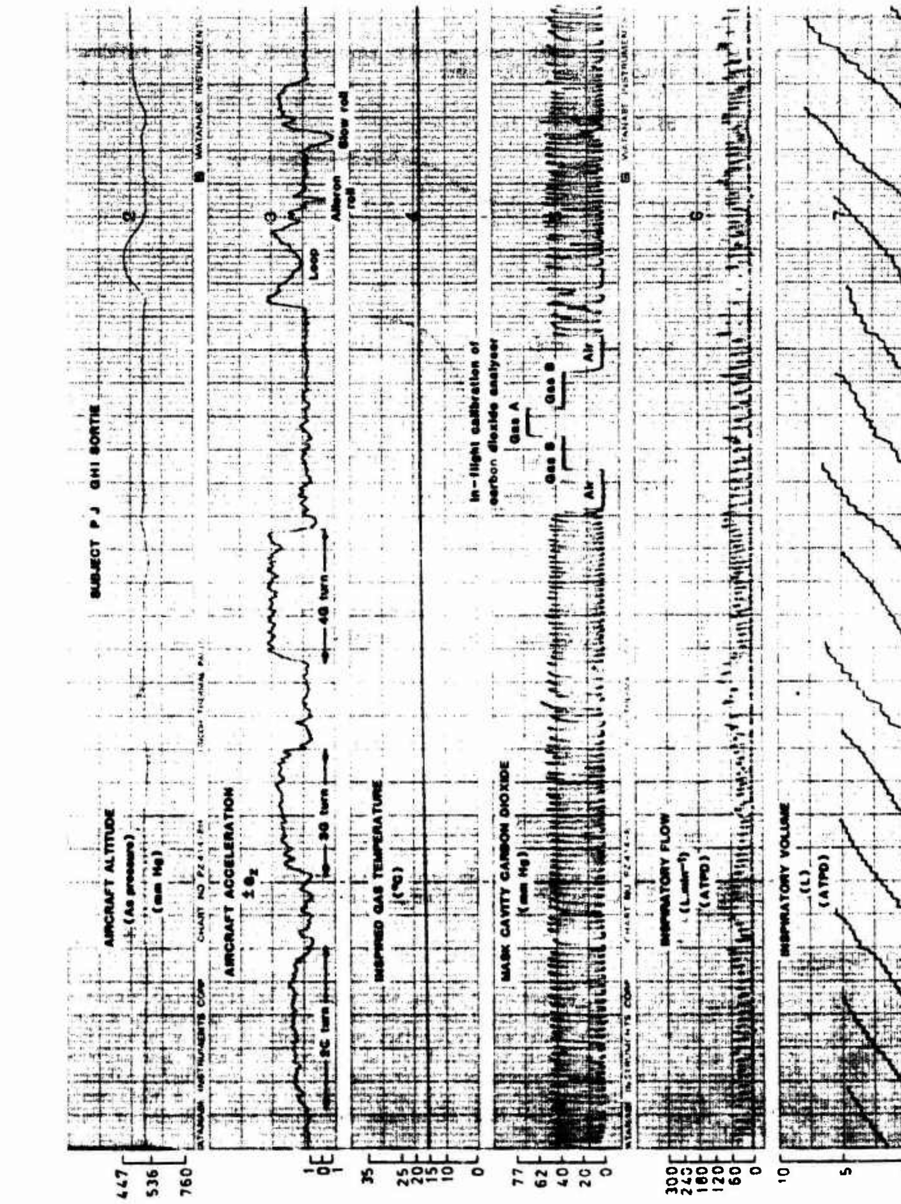


Figure 3.5 Reproduction of part of a typical in-flight record, including an in-flight calibration of the carbon dioxide anlyser

Analysis of all pre-flight, in-flight and post-flight calibrations showed most of them to be linear, with 169 of the 184 sets having correlation coefficients of 0.9975 or better. The individual correlation coefficients for all calibration sets are listed at Appendix C, (pA4). Preliminary analysis of $P_{ET}CO_2$ during three consecutive sorties (40,41,42) revealed errors in both the pre-flight and post-flight calibrations and these data have been discarded from the final analysis of this variable. The problem was traced to a faulty solenoid switch and, after servicing, the analyser again functioned correctly.

The experimental equipment produced no subjective problems for the pilots and was reported as entirely acceptable. The unusual geometry of the mask inlet hose was initially felt by some subjects to lift the lower edge of the mask away from the face, particularly when looking down into the cockpit, so breaking the all-important mask-to-face seal. Scrutiny of the inspiratory flow and carbon dioxide/mask cavity pressure records, however, demonstrated that, in all subjects except one, the mask was sealed against the face throughout flight. The single exception also achieved a correct seal during those periods of flight requiring increased mental and physical effort, but the records during the routine phases (taxy, take-off, climb, cruise, descent and landing) of two of his three flights were seriously degraded and were unusable (sorties 14 and 40).

No in-flight incidents or emergencies occurred during the study and no emergency procedures were needed.

The data were extracted and analysed as described in detail below and as summarised in the flow chart at Figure 3.6.

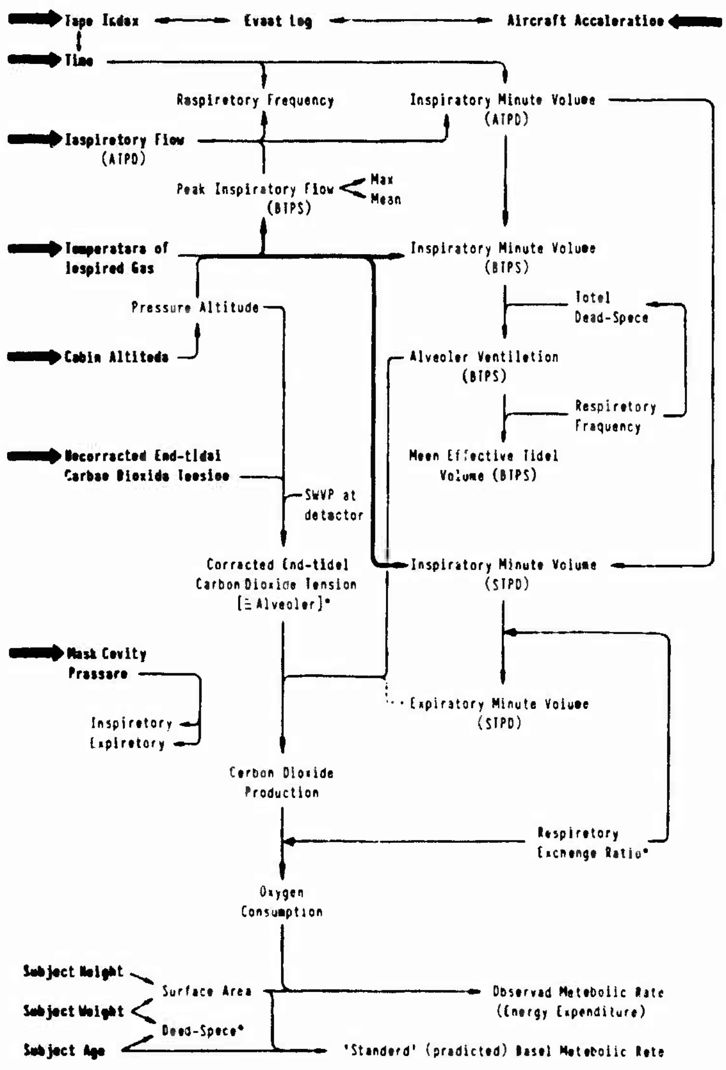


Figure 3.6
Sequence of analysis of derived variables from those recorded
*[For assumptions see text p57]

Two approaches to analysis of the raw data were adopted. The first, more traditional, method was used to determine respiratory frequency and inspiratory minute volume, and involved division of each sortie into consecutive units each of one minute duration. The start point was arbitrarily set at the beginning of the physiological record, ie when recorded respiratory responses began. For the purpose of comparison, each unit was then allocated to one of 24 identifiable phases of flight (based on the flight log and the aircraft acceleration profile): the allocation being to that phase which most occupied the minute concerned since, clearly, arrangement of the phases of flight into precise temporal blocks was not possible. The 24 phases (listed in Table 4.2c, p39) comprised 9 which occurred during **routine** flight and 15 which occurred during **manoeuvring** or applied flight: most of the former were identified in all sortie types while occurrence of the latter varied with sortie profile. Later, certain of the phases were combined, on the basis of similar patterns of acceleration, so increasing the numbers available for statistical treatment. For each recorded variable for each flight, a calibration look-up chart, based on the polynomial distribution of calibration values, including those obtained in-flight, was generated by computer. The charts gave conversion values for each block deflection on the paper trace and these corresponded closely with values obtained from calibration charts generated by hand. The look-up charts were used for manual reduction of data in minute blocks.

The second approach to analysis was to digitize both in-flight data and calibrations for each flight record. This method was used primarily for breath-to-breath assessment of mask cavity pressure, inspiratory peak flow and end-tidal carbon dioxide tension, but the other traces were also digitized: inspired gas temperature and cabin altitude to provide correction factors for the physiological variables; aircraft acceleration and cabin altitude to provide support for the in-flight log and a comparison between flights.

An ultrasonic digitizer ('Graf Pen' 8 Sonic Digitizer, Science Accessories Corporation) was used in conjunction with a micro-computer (British Broadcasting Corporation Model B) and supported by specially written software. Each calibration set and each in-flight trace was digitized and the information stored on floppy disk. The data were then transferred to a mainframe computer (H500 Supermini, Harris Computer Systems) for conversion and analysis. The analytical software first generated a conversion file from the digitized calibration points and then converted the appropriate digitized in-flight sequence to raw values. For aircraft acceleration, inspired gas temperature and cabin altitude (as pressure), the temporal spaces between digitized values were filled by linear interpolation. Discrete values were obtained for inspiratory peak flow, inspiratory minute volume, end-tidal carbon dioxide tension and minimum/maximum mask cavity pressures. Where necessary, the appropriate correction factors (eg to BTPS conditions) were applied. For each variable, a time axis was generated, the data having been digitized in one minute blocks, and a continuous record for the entire sortie created both numerically and graphically. Examples of the latter are shown at Figure 3.7. Comparison of 100 derived values for minute volume, obtained by the first (whole minute analysis) approach, with the equivalent values obtained by digitization showed there to be agreement between the methods to within +/-2.5%. Agreement to within +/-7.5% existed when 200 randomly-chosen values of inspiratory peak flow, obtained by digitization, were compared with manually extracted values.

<u>3.2.2 Analysis of Recorded Variables</u>. **Respiratory Frequency** was assessed from deflections of the inspiratory flow signal, while **Inspiratory Minute Volume** was obtained by electronic integration of the flow signal. Electronic calibration of the integrator showed there to be no discernible error in the device itself; errors, if any, in the flow/volume measurements therefore lay within either the pneumatic and transducing equipment or the experimental procedures and are discussed below, (p36). Minute volumes were converted from ATPD to BTPS values by equation [2], assuming the inspired gas to be dry.

$$\dot{V}_{I(BTPS)} = \dot{V}_{I(ATPD)} \cdot \frac{273 + 37}{273 + t_{amb}} \cdot \frac{P_B}{P_B - 47} \qquad [2]$$

Inspiratory Peak Flow was measured for all breaths from all sorties by digitizing the maximum deflections on the inspiratory flow trace. Peak flows were converted from ATPD to BTPS values by equation [3] (analogous to equation [2]), again assuming the inspired gas to be dry.

$$\hat{\dot{V}}_{I(BTPS)} = \hat{\dot{V}}_{I(ATPD)} \cdot \frac{273 + 37}{273 + t_{amb}} \cdot \frac{P_B}{P_B - 47} \qquad [3]$$

Breath-to-breath **End-tidal Carbon Dioxide Tension** was determined by digitizing the maximum deflections on the carbon dioxide analogue record. These tensions were measured by the carbon dioxide analyser at ambient pressure and at a temperature, inside the analyser, of 26°C (SWVP at 26°C = 25.2 mmHg (3.36kPa)), and may thus be regarded as 'uncorrected'. The data were corrected to body conditions by equation [4].

$$\underset{(corrected)}{P_{ET}CO_2} = \underset{(uncorrected)}{P_{ET}CO_2} \cdot \frac{P_B - 47}{P_B - 25.2} \qquad [4]$$

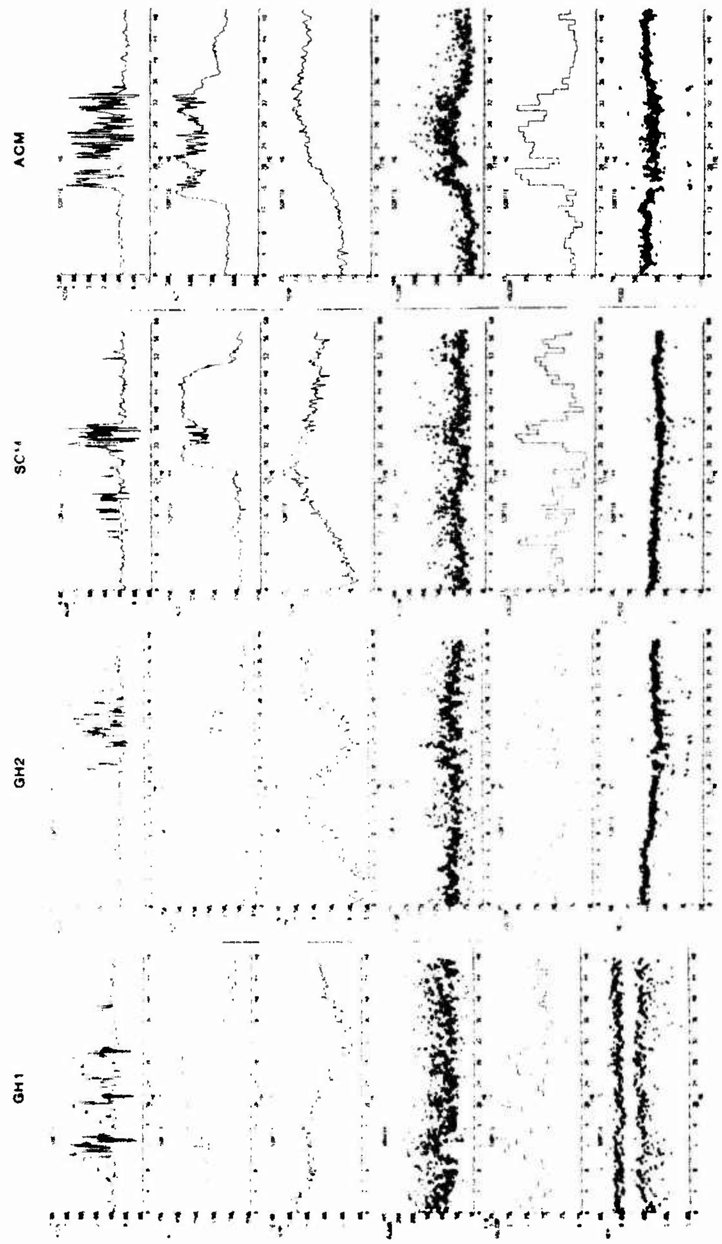


Figure 3.7 Examples of computer-generated plots of in-flight variables
(data derived from digitized flight records)

[ACCN is aircraft acceleration (+/- Gz); ALT is cabin altitude, as pressure (mmHg); TEMP is inspired gas temperature (^{o}C); FLCOR is peak inspiratory flow (L(BTPS).min $^{-1}$); VOLCOR is inspiratory minute volume (L(BTPS).min $^{-1}$); MCP is mask cavity pressure (in water); PCO2 is end-tidal carbon dioxide tension (mmHg)]

3.3 Experimental Errors

No measurement can ever be made with absolute accuracy and, as with all biological experimentation, errors in the results of this study could have originated in a multitude of ways; not all of which were amenable to precise examination. Thus, it was clearly not possible to identify or quantify those accidental or random errors the causes of which were unknown, but which are a natural accompaniment of any experimental procedure (eg mis-reading of scales, faulty transcription and simple errors of omission). Fortunately, such errors can be largely eliminated if sufficient care is taken, and this was strongly emphasised to all those involved in the support of this study. Accidental errors will not be considered further. As explained below (p59), the influence of errors introduced by the assumptions made to facilitate calculations could not be quantified in all cases, and is likewise not discussed further here.

Systematic errors, that is those associated with particular instruments or techniques of measurement, and those resulting from external conditions, are however open to examination. In the present study, instrumental errors were reduced as far as possible by careful choice of measuring devices and transducers, repeated measurements of linearity and response times, and repeated careful calibration; while external or environmental errors, such as those due to the effects of temperature and pressure changes, were eliminated by direct measurement of the variables concerned and subsequent correction of the data. The choice and behaviour of the Fleisch pneumotachograph and of its associated pressure tranducer has been discussed above (p30), and no error was detectable in their combined performance over the range of relevance. Particular care was taken to avoid pressure artefacts, and hence artificially high peak flows, as a result of volume inbalance across the pneumotachograph head and transducer, such as may be seen during sharply varying flow wave-forms. Since the gas delivered by the LRBS was assumed to be dry (p59), no reduction in observed flow occurred as a result of the presence of water vapour. The integrator also had no discernible error (p34) and there was, therefore, no observable instrumental error in the pneumotachograph-tranducer-integrator circuit; although an unquantifiable error in the electronic components must have existed. Details of the carbon dioxide analyser were given above (p20), and the maximum instrumental error was assumed to be that deduced from the results of its comparison with the mass spectrometer (p30), ie +/-2.5%. Although the magnetic tape recorders, with their implied accuracy of the IRIG standard, were regarded as accurate to within +/-0.35%, and the pen recorders were appropriately responsive, it was in the reading of the permanent record that most quantifiable errors could be isolated. It was estimated that the traces could be read, whether by eye or by the digitizer pen, to a resolution of 1/4 of a block. With a full-scale deflection of ~ 80% imposed for each calibration signal, the mean percentage error for each of the recorded physiological/environmental variables was as follows:

	Calibrated Range	% Error
Barometric pressure	513	+/- 0.78%
Inspired gas temperature	35	+/- 0.76%
Inspiratory flow	300	+/- 0.95%
Inspired minute volume	5	+/- 0.80%
Carbon dioxide	77	+/- 0.86%
Mask cavity pressure	10	+/- 0.79%
Aircraft acceleration	2	+/- 3.38%

The instrumental and measurement percentage errors were read across into the appropriate equations in accordance with the rules of error analysis, to yield systematic errors for each of the major derivations, thus:

$\dot{V}$, ATPD to BTPS values (Eqn [2]), error	= +/- 2.87%
$\dot{V}$, ATPD to BTPS values (Eqn [3]), error	= +/- 3.02%
Uncorrected $P_{ET}CO_2$ to corrected (Eqn [4]), error	= +/- 5.25%
$P_{ET}CO_2$ to VCO_2 (STPD) (Eqns [11] & [12]),* error	= +/- 9.63%
Energy expenditure (Eqn [14]),* error	= +/- 9.63%

[* see p53]

For instrumental errors and errors of measurement it was therefore concluded that, in the worst case, the maximum percentage error for the equations derived was +/-9.63%; well within the generally accepted limits of physiological measurement.

A further, intangible, source of error lay within the arbitrary and subjective allocation of event to one minute time-spans, regardless of the duration of the event. Some manoeuvres, such as loops and rolls, lasted for seconds only, while others, such as sustained high +Gz turns, occasionally lasted longer than one minute. The effect of this method of allocation was maximal during events of the first type when physiological responses to the manoeuvre diluted, or were diluted by, periods of 'normality' before and after. The magnitude of this factor varied from one type of event to another and between similar events occurring at different times, for different times, and was therefore impossible to quantify. Some indication of the order of error was given by a more detailed temporal analysis carried out for certain flight phases. This suggested that, for example, peak inspiratory flow during +4Gz turns was over-estimated, by the allocation method, by 3.0% while end-tidal carbon dioxide tensions were over-estimated by 3.3%; both over-estimates being the result of higher values of these variables occurring before and after the manoeuvre itself.

3.4 Statistical Considerations

A comprehensive analysis of variance was conducted upon the raw data, the details and results of which are given at Appendix D (pA4 et seq). The only measures of statistical validity given in the body of Part 4 of this study (Results and Discussion) are those of the significance of differences, if any, between sets of measurements; ie probabilities or P values. Overall standard deviations are deliberately not quoted since they are functions of circumstances and not absolute measurements. In comparisons of physiological data, even in well-balanced studies, such figures are based on several components of a random nature. In this study, which was not well-balanced, these components are clearly distinguished in the analysis of variance (subject and subject by flight profile). To quote them as single figures, as an indication of physiological variation, would be meaningless.

The analysis of variance, based on data acquired from in-flight recording and reduced as described above (p31 et seq), showed there to be no major inconsistencies in the figures; that is, that the data may be regarded as sound (experimental errors notwithstanding).

Part 4 - RESULTS AND DISCUSSION

4.1 Respiratory Responses During High Performance Flight

4.1.1 General. All 46 flights yielded usable physiological data. The total duration of the records was 38.4 hours and included over 47,000 breaths. Table 4.1 lists the types of experimental flight flown by each subject, while further essential details of individual sorties are listed at Appendix E, (pA17).

Subject	Sortie Type: G H 1	G H 2	S C M	1 v 1 A C M	Total
1st Phase (RAE)					
MB	✓		✓		2
HM	✓		✓		2
GW	✓		✓		2
RR	✓		✓		2
AA	✓		✓		2
JA	✓		✓		2
2nd Phase (TWU)					
PJ	✓*	✓	✓*		3
SW	✓*	✓*	✓		3
KB	✓*	✓	✓		3
DM	✓*	✓*	✓*		3
AS	✓*	✓	✓*		3
PS	✓*	✓*	✓*		3
MA	✓*	✓*	✓		3
DH	✓		✓		2
JF	✓*	✓*	✓*	✓*	4
LB	✓*	✓*	✓		3
RB	✓				1
DF	✓		✓*	✓*	3
Total	18	9	17	2	46
* = with CO2 analysis	9	6	6	2	23

Table 4.1 Summary of experimental flights flown by each subject

4.1.2 Respiratory Frequency, Inspiratory Minute Volume and Peak Flow.

Respiratory Frequency. The mean control value for resting respiratory frequency in this group was 11.3 breaths.min^{-1}, and accords well with some older 'textbook' resting normal values of 10-14 breaths.min^{-1}.[110,111] Such levels were determined from instrumented subjects and so were probably affected by additional dead-space and added external resistance. They are therefore directly comparable to resting values reported here. It should be remembered, however, that Mead has reported that covert observation of subjects unhindered by instrumentation suggests that normal resting levels may be as high as 16 - 20 breaths.min^{-1} and that the knowledge that experimental observations are being made leads to an involuntary reduction to the familiar, slower and more regular 'normal' frequency.[112] This possibility is reflected in tables of normal values published more recently, eg 12 - 20 breaths.min^{-1} by Cotes in 1979.[113]

A total of 2,304 minutes of flight records was analysed and the frequency distribution of the values obtained is shown at Figure 4.1. The un-weighted mean respiratory frequency for all phases of all sorties was 20.5 breaths.min^{-1}. There was no significant difference between the mean values for the RAE test pilots and those for the TWU squadron pilots, nor were there significant differences between overall mean values for different sortie types. There was, however, a significant difference between the mean respiratory frequency during routine phases of all types of sortie and that during manoeuvring phases, (overall means of 19.1 and 22.8 breaths.min^{-1} respectively: $P < 0.0005$). Table 4.2 lists these results in detail, together with the results for individual phases of flight. Figures 4.2 a, b and c show the results graphically for all phases combined, for routine vs manoeuvring phases and for individual phases respectively.

Mean respiratory frequencies were highest during ACM and high-G manoeuvres, with a mean value of 26.7 during ACM and 27.4 breaths.min^{-1} during +6G spirals. All of these findings, and particularly those during routine flight, correlate well with previously published data (Table 1.1, p6) with the exception of the remarkably high respiratory frequency (70.min^{-1}) reported on take-off in one subject flying a high altitude balloon.[11] The length of time for which this level was sustained was not reported. In the present study, only five pilots produced respiratory frequencies of 35 breaths.min^{-1} or over and only then on a total of 12 occasions during high G manoeuvres or recovery therefrom, and never for longer than two consecutive minutes. The highest respiratory frequency recorded was 43 breaths.min^{-1} on one occasion. The large difference between resting values and those seen during even routine flight is a reflection of the physiological cost of the flying task.

a. Analysis of whole sorties

	Respiratory Frequency (.min⁻¹)		Minute Volume (L(BTPS).min⁻¹)	
	f	n	MV	n
GH1(RAE)	19.9	265	15.2	265
GH1(TWU)	20.1	637	19.3	637
GH1(All)	20.0	902	18.1	902
GH2	20.5	502	19.3	463
SCM(RAE)	21.5	256	17.0	256
SCM(TWU)	20.8	544	19.5	507
SCM(All)	21.0	800	18.7	763
ACM	19.7	100	22.5	100
TOTAL	20.5	2304	18.8	2228

b. Analysis of Routine vs Manoeuvring Phases

	Respiratory Frequency (.min⁻¹)				Minute Volume (L(BTPS).min⁻¹)			
	Routine		Manoeuvring		Routine		Manoeuvring	
	f	n	f	n	MV	n	MV	n
GH1(RAE)	18.6	143	21.3	122	13.2	143	17.5	122
GH1(TWU)	19.0	391	21.9	246	18.3	390	20.9	247
GH1(All)	18.9	534	21.7	368	17.0	533	19.8	369
GH2	19.5	295	21.9	207	18.5	262	20.3	201
SCM(RAE)	19.9	169	24.7	87	14.0	169	22.8	87
SCM(TWU)	19.3	401	24.9	143	18.0	368	23.6	139
SCM(All)	19.4	570	24.8	230	16.7	537	23.3	226
ACM	16.1	65	26.3	35	17.6	65	31.8	35
TOTAL	19.1	1464	22.8	840	17.2	1397	21.4	831

c. Analysis by Phase

Phase	Respiratory Frequency (.min⁻¹)		Minute Volume (L(BTPS).min⁻¹)	
	f	n	MV	n
Strap-In	18.2	181	18.2	175
Taxy (pre)	19.0	199	18.7	188
Take-Off	18.8	46	18.9	44
Climb	18.8	246	16.0	237
Cruise	18.5	242	15.7	228
2G Turns	20.7	72	17.1	72
3G Turns	22.4	66	19.1	66
4G Turns	23.7	52	20.5	52
Loops	24.0	48	23.3	48
Rolls	22.5	58	22.3	58
Aerobatics	24.5	58	23.5	57
High G Spirals	24.6	30	21.2	30
6 G Spirals	27.4	45	25.0	43
Level Turns	25.1	44	22.6	41
Barrel Rolls	25.0	23	24.6	23
Low Level	20.7	121	18.9	119
Steep Turns	20.0	21	17.6	21
Wind-up Turns	23.8	9	22.6	9
ACM	26.7	30	32.8	30
Recovery	21.4	163	21.3	162
Descent/RTB	19.4	287	16.1	276
Circuits	21.4	138	19.1	131
Land	19.8	41	17.9	39
Taxy (post)	19.4	84	18.8	79

Table 4.2
Respiratory Frequency and Inspiratory Minute Volume
Un-weighted mean results of minute analysis

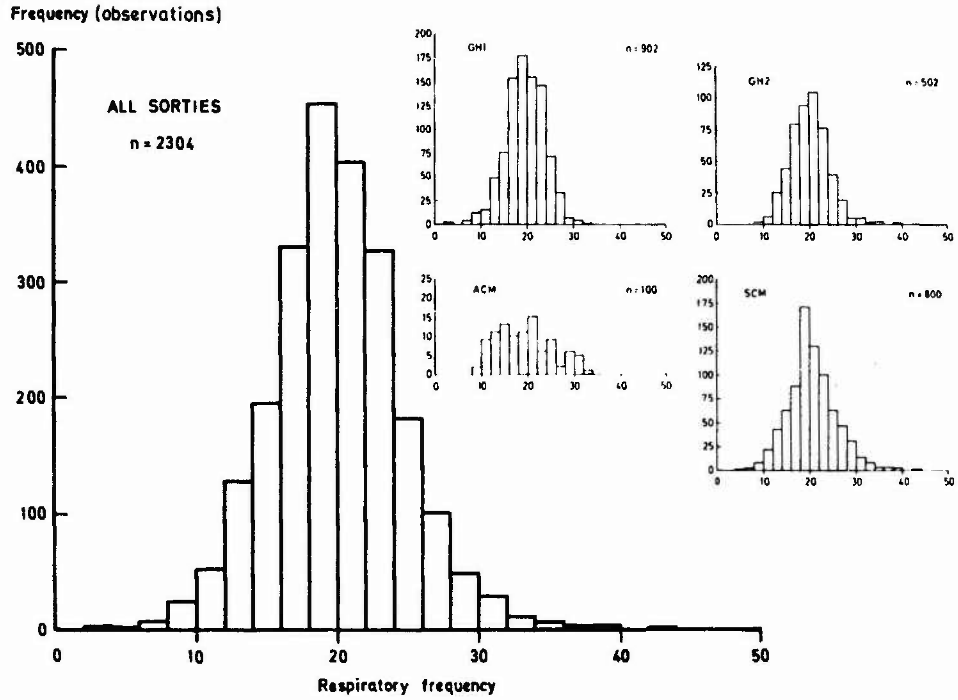


Figure 4.1 Frequency distribution for respiratory frequency: all sorties combined
(Inset: frequency distributions for individual sortie types)

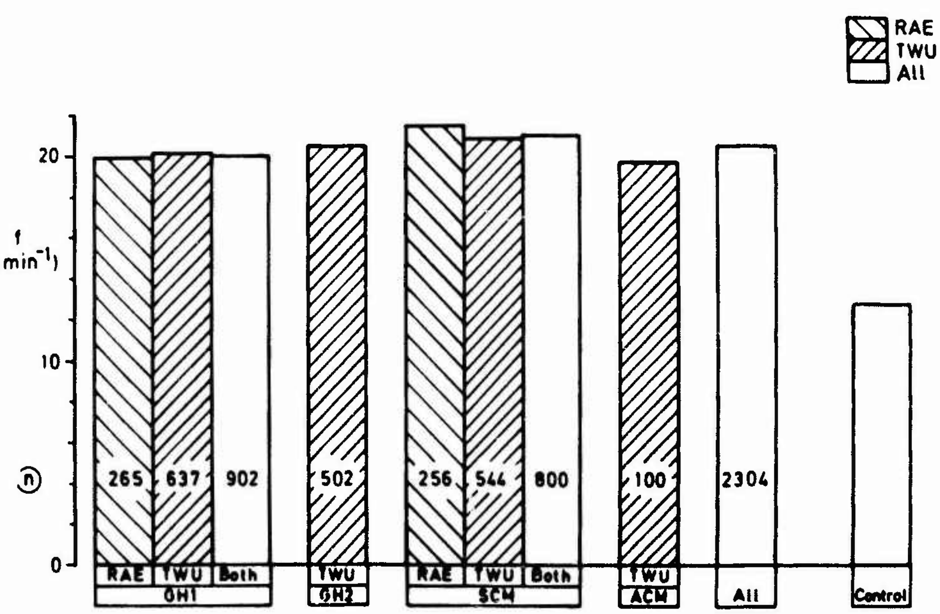


Figure 4.2a Respiratory Frequency
Un-weighted mean results of minute analysis all phases combined

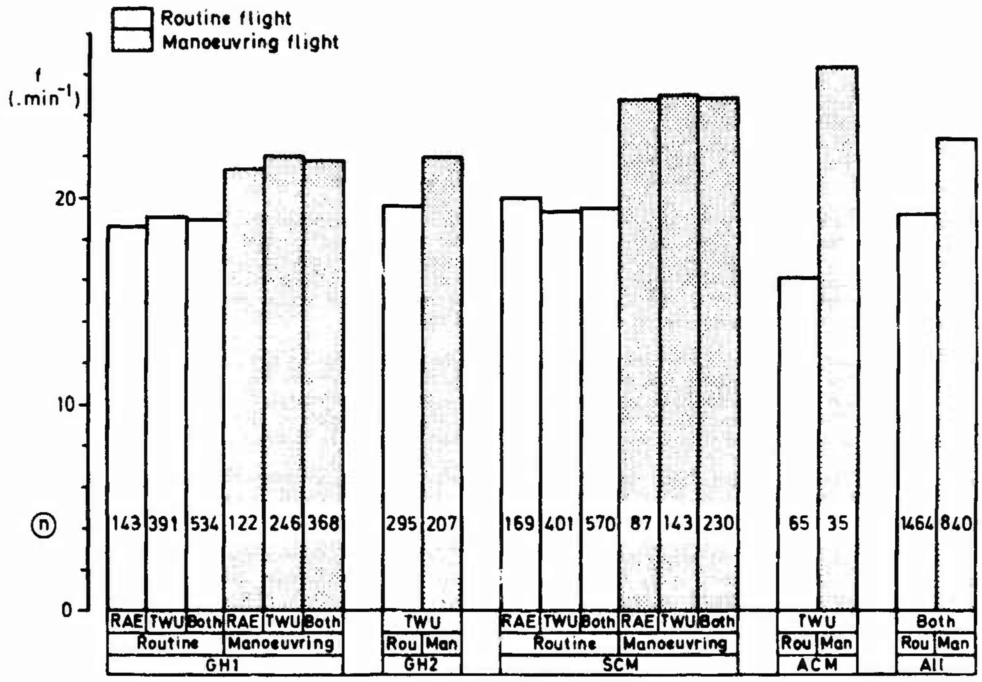


Figure 4.2b Respiratory Frequency
Un-weighted mean results of minute analysis: routine vs manoeuvring phases [Rou = Routine, Man = Manoeuvring]

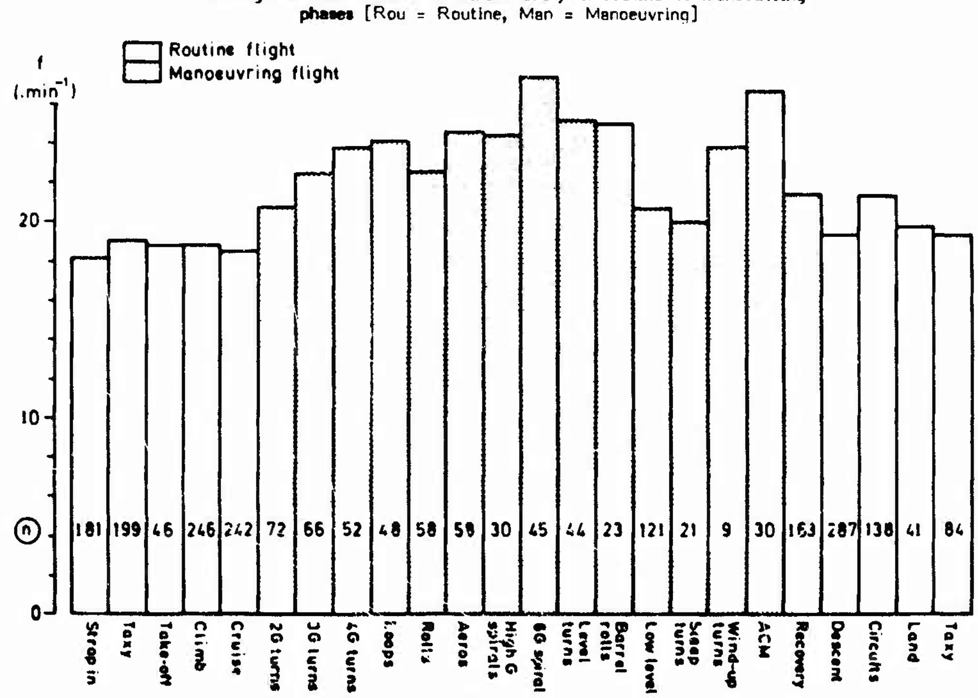


Figure 4.2c Respiratory Frequency
Un-weighted mean results of minute analysis: individual phases

Inspiratory Minute Volume. For this group, the mean control (resting) value for minute volume was 9.9L(BTPS).min^{-1} and so was in agreement with textbook normal values of 6.0 - 10.0L(BTPS).min^{-1}.[113, 121]

The frequency distribution of the in-flight results obtained is shown graphically at Figure 4.3, while Table 4.2 (p39) lists the un-weighted mean results for inspiratory minute volume (BTPS) during all phases combined, during routine vs manoeuvring phases and during individual phases. The overall mean ventilation for all phases of all sorties was 18.8 L.min^{-1} but a significant difference was demonstrated between the mean minute volume of the pilots from the RAE and that of those from the TWU: the latter produced higher levels both overall (for combined phases of GH1 and SCM sorties - Figure 4.4a) and for routine and manoeuvring phases (Figure 4.4b). The difference was most marked, however, during routine flight (eg 13.2L(BTPS).min^{-1} cf 18.3L(BTPS).min^{-1} for RAE and TWU pilots respectively during routine phases of GH1 sorties (P <0.0005))

The reason for this difference is not clear and, although it may be expected that the RAE test pilots would ventilate at a lower level than their squadron colleagues at times of mental stress, by virtue of their experience and greater familiarity with unusual (experimental) flight conditions, this would not explain why there should be such a marked difference in the absence of overt mental stress (routine flight) or during the same physical stress (manoeuvring flight). Furthermore, many of the TWU pilots were as experienced, or more so, than the test pilots; although not of course with experimental flying.

Figure 4.4c shows the mean minute volume results for individual phases. Once again, high G manoeuvres and ACM produced the highest minute volumes, the latter markedly so at a mean value of 32.8L(BTPS).min^{-1}, and there was a clear direct relationship between the intensity of the manoeuvre, in terms of degree of applied acceleration, and mean minute volume. The highest minute volume recorded in this study, 42.25L(BTPS).min^{-1}, occurred during recovery from high G manoeuvres on one occasion and was not sustained.

Inspired minute volumes during flight have only been described on two previous occasions. In 1964, Norris[39] reported a mean minute volume of 13 - 14L(BTPS).min^{-1} for subjects flying a routine training mission in a jet bomber, with no manoeuvring phases; a figure which correlates very well with that reported here for RAE pilots during routine flight. In the other study, by Macmillan et al in 1976[42], mean minute volume did not exceed 22L(BTPS).min^{-1} during straight and level flight, but an overall mean value was not reported. The mean value of 15.7L(BTPS).min^{-1} seen in the cruise phase of the present study cannot therefore be compared directly. When the mean minute volumes seen during all routine phases of flight (taxy, take-off, cruise, approach and landing) are compared with previously reported expiratory minute volumes during similar phases (Table 1.1, p6) a close correlation is seen to exist. Only one of these reports, however, (that of Morgan et al in 1976), refers to modern jet fighter aircraft and, in that case, mean minute volume during cruise was lower than the level seen here (5.0 - 11.8L(BTPS).min^{-1}).[39] The mean value of 26L(BTPS).min^{-1} reported by Macmillan et al during 'aerobatic' flight may be compared, although loosely, with a mean value of 21.4L(BTPS).min^{-1} seen in the present study for all manoeuvring phases combined. Closer agreement is seen when discrete manoeuvring phases are compared. Thus, for loops, level turns and barrel rolls, the mean minute volumes were 23.3, 22.6 and 24.6L(BTPS).min^{-1} respectively in the present study, compared with 19.9, 22.2 and 18.9L(BTPS).min^{-1} reported earlier. No other data are available for minute volumes of subjects in military aircraft during such flight.

These results are in accord with those from studies using man-carrying centrifuges, which also demonstrated an increase in minute volume under +Gz conditions and attributed it to a combination of increased respiratory frequency and increased tidal volume.[121, 124] The increases were modest at levels up to +3Gz but could be as great as 150% of resting levels at >+5Gz. The even greater increases seen in the present study were presumably due to the combination of factors operating in addition to the level of applied acceleration, and again reflect the physiological cost of flying an aircraft (ie the increased energy cost of muscular activity) during all phases of flight.

Inspiratory Peak Flow (and Mask Cavity Pressure). The mean control (resting) value for peak inspiratory flow for this group was 37L(BTPS).min^{-1}. The frequency distribution of peak inspiratory flows seen during flight is shown at Figure 4.5. Over 7.4% of the 47,141 breaths had peak flows above 150L(BTPS).min^{-1} and 0.25% were greater than 250L(BTPS).min^{-1}. The highest peak inspiratory flow seen in this study was 384.6L(BTPS).min^{-1} but a further 24 (0.05%) were above 300L(BTPS).min^{-1}. These figures correlate well with the maximum peak inspiratory flows (under ATPS conditions) of 300L.min^{-1} reported by Comroe et al[121] and by Silverman et al.[44] The latter were obtained under conditions of maximum exertion on a cycle ergometer in the laboratory, whereas those recorded in the present study were from sitting subjects, albeit under moderate, but transient, stress. This implies that a physiological maximum is being approached during very hard work. When peak inspiratory flows were meaned over each one minute period, and the results aligned with the minute-by-minute analysis data, the mean peak inspiratory flow for all phases of all sorties was 89L(BTPS).min^{-1}. This may be compared with a mean value of approximately 70L(BTPS).min^{-1} reported in the study by Macmillan et al[42], involving over 7,000 breaths. The mean value during manoeuvring phases was 96L(BTPS).min^{-1}, with ACM producing the highest mean of 144L(BTPS).min^{-1}. The overall mean value for routine phases of flight was 84L(BTPS).min^{-1}. Figures 4.6a, b and c illustrate the mean values for peak inspiratory flow for all flight phases combined, for routine vs manoeuvring flight and for individual phases respectively.

Also included in these Figures are mean values for the maximum peak inspiratory flow seen during each minute of the various flight phases and combinations of phases. When the data were analysed in this way, the mean maximum peak inspiratory flow for all phases was 152L(BTPS).min^{-1} while those for routine and manoeuvring flight were 146 and 163L(BTPS).min^{-1} respectively. Of the individual phases, ACM produced the highest mean maximum flow, at 218L(BTPS).min^{-1}, followed by aerobatics at 196L(BTPS).min^{-1}. The mean values of all inspiratory flow results are included in Table 4.3, p48.

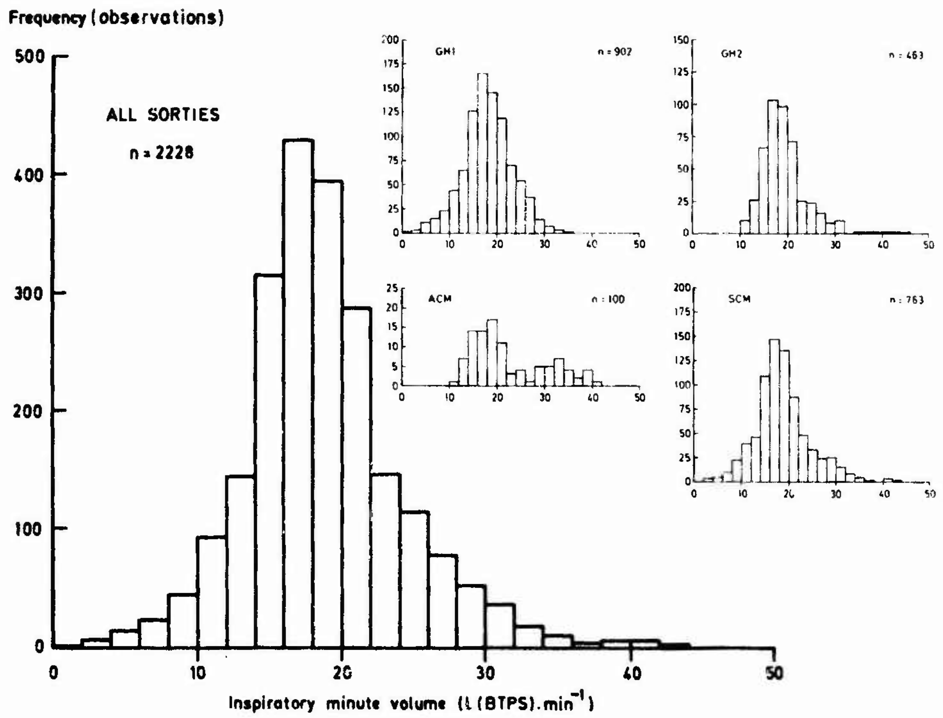


Figure 4.3 Frequency distribution for inspiratory minute volume: all sorties combined
(Inset: frequency distributions for individual sortie types)

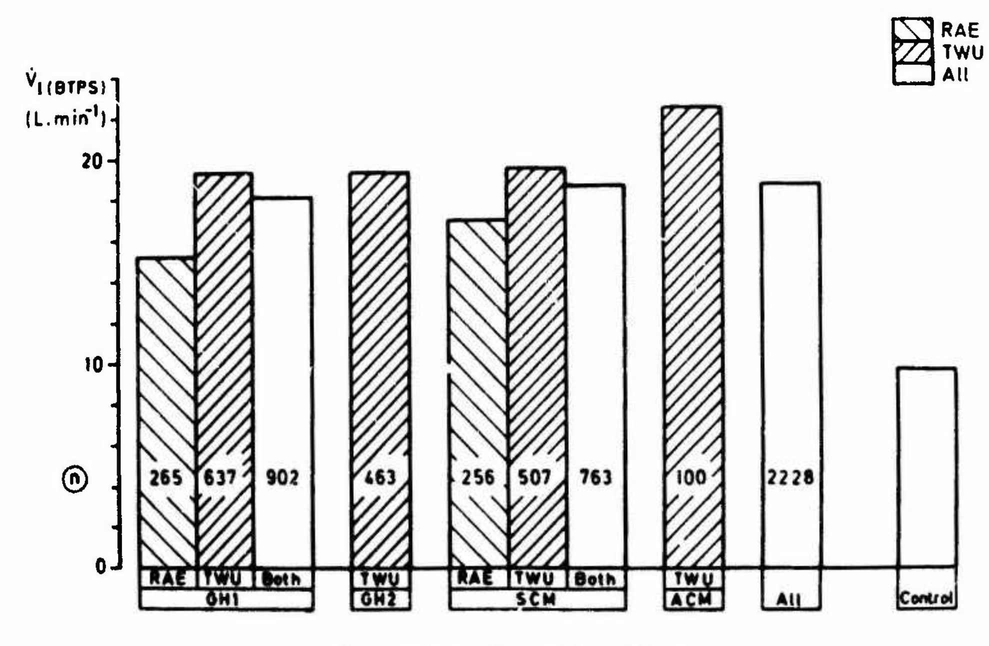


Figure 4.4a Inspiratory Minute Volume
Un-weighted mean results of minute anlysis: all phases combined

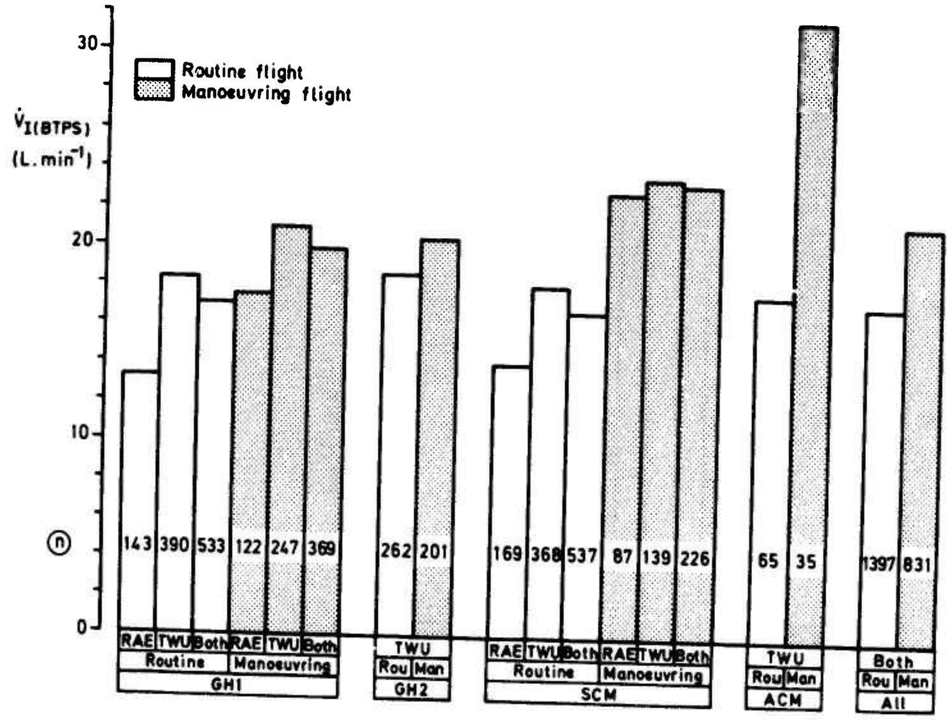


Figure 4.4b Inspiratory Minute Volume
Un-weighted mean results of minute analysis: routine vs manoeuvring phases

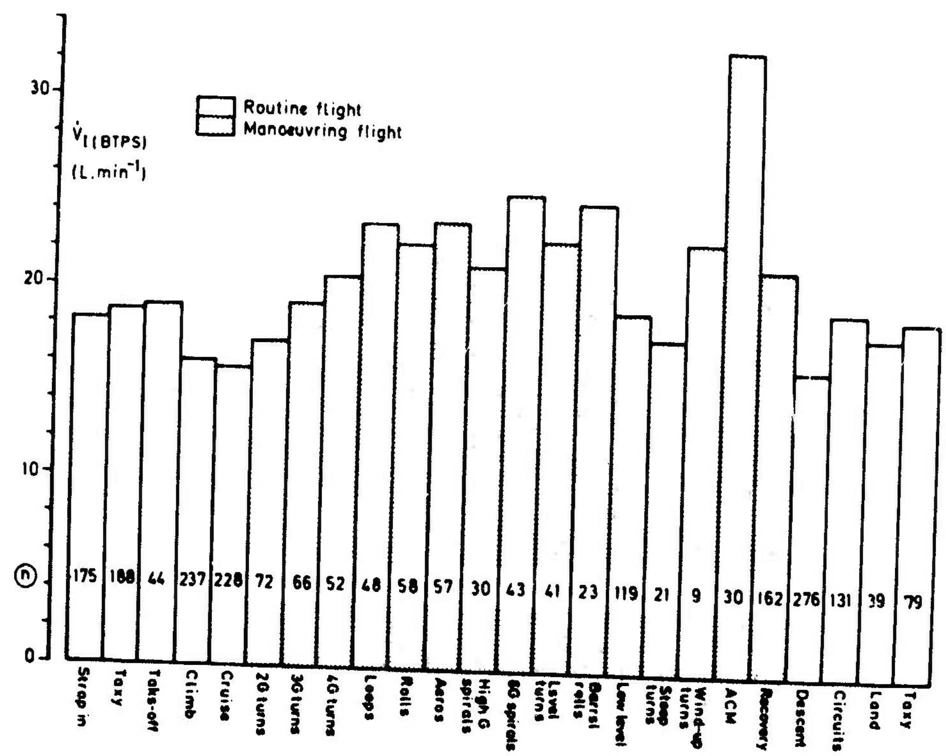


Figure 4.4c Inspiratory Minute Volume
Un-weighted mean results of minute analysis: individual phases

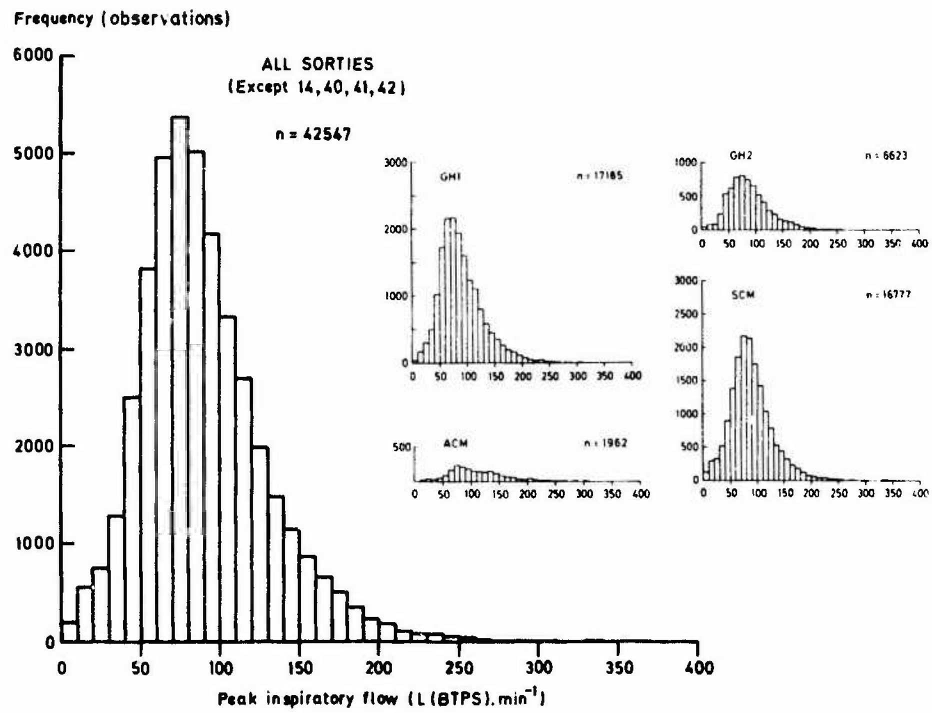


Figure 4.5 Frequency distribution for peak inspiratory flow: all sorties combined
(Inset: frequency distributions for individual sortie types)

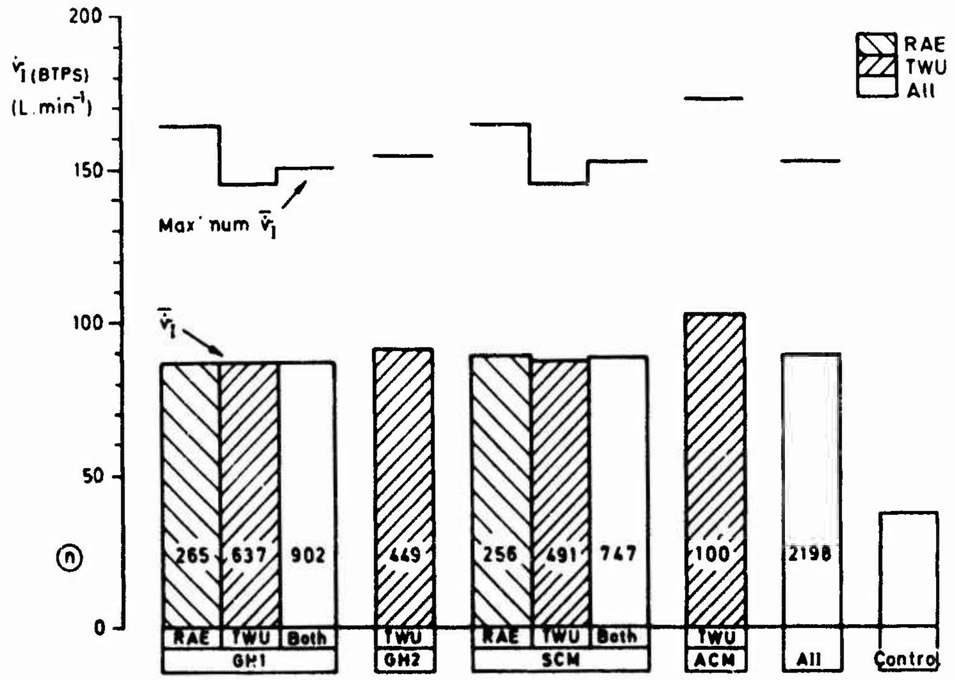


Figure 4.6a Peak Inspiratory Flow
Un-weighted mean results of minute analysis: all phases combined
[see text (p47) for explanation of maximum $\dot{V}_I$]

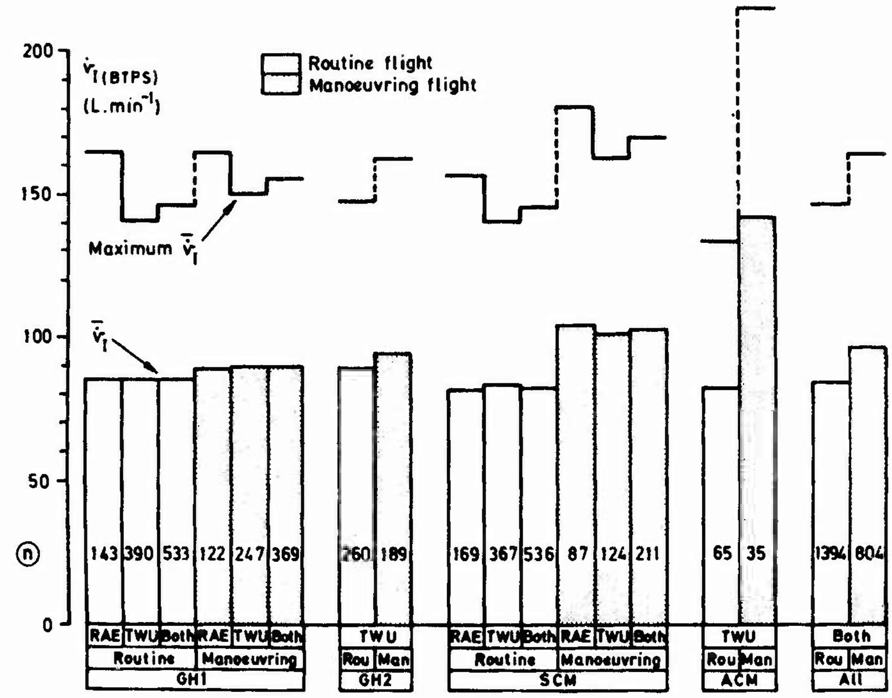


Figure 4.6b Peak Inspiratory Flow: Un-weighted mean results of minute analysis: routine vs manoeuvring phases

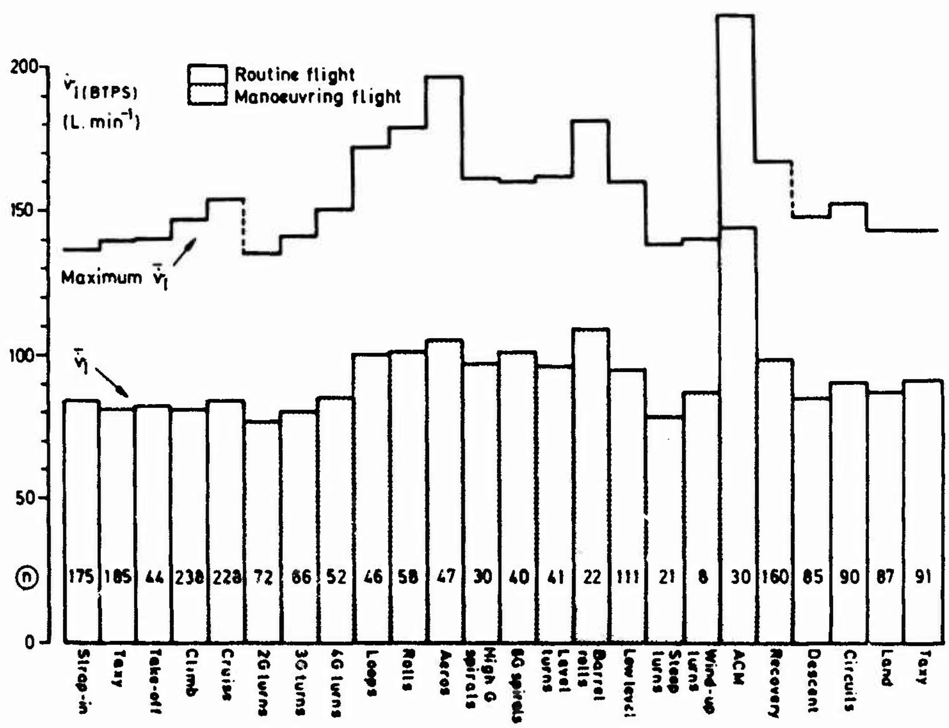


Figure 4.6c Peak Inspiratory Flow
Un-weighted mean results of minute analysis: individual phases

Silverman et al [44] found the ratio of the mean peak inspiratory flow (in their case derived by dividing the minute volume by the ratio of inspiratory cycle time to total respiratory cycle time) to the mean maximum peak inspiratory flow to be a useful concept when describing respiratory behaviour in the presence of added external resistance. The ratio, when expressed as a percentage, was said to give an indication of that proportion of the inspiratory phase during which flow is at the optimum (most efficient) for a system with that resistance. With no added resistance the ratio was found to be 66%, suggesting that flow was sustained at two thirds maximum during the period under consideration. The ratio was fairly constant for a given workload but linearly related to the magnitude of added resistance. For example, with added inspiratory resistances of 2.5, 7.6, 10.2, and 20.3 cm water (0.24, 0.74, 1.0 and 1.98kPa), at a flow of 85L.min^{-1}, the ratios increased to 72%, 74%, 77% and 82% respectively, demonstrating a reduction in maximum flow acheivable in the face of increased inspiratory resistance. For the LRBS, the overall ratio was 58%, as might be predicted of a low resistance device, and, even at the high flows seen during ACM and other manoeuvring phases, the ratio did not exceed 66% (Table 4.3). This indicates that the LRBS behaved in flight as was hoped, as a breathing system imposing a low external added load. The technique of relating inspiratory flows in this way may thus provide a method of gauging the added inspiratory load of a system without the need to measure mask cavity pressure.

The paper by Macmillan et al [42] was the only previous study to have reported values for peak inspiratory flow in flight and it is probable that the higher mean peak flow reported here is the result of the reduced external resistance offered by the LRBS. The breathing system used by Macmillan et al was a standard RAF installation and included a P/Q series oxygen mask with the resistance characteristics illustrated in Figure 3.1, p28. In-flight recordings of mask cavity pressure in this study supported the laboratory findings and confirmed that the LRBS was functioning correctly as a low resistance device whenever mask pressure was being monitored and thus throughout the 46 flights. Minimum mask cavity pressure during inspiration was directly proportional to inspiratory flow and this almost linear relationship is illustrated at Figure 4.7. There was no difference in the magnitude of this relationship for the two subject groups. At no time did the minimum pressure of inspiration in the mask exceed -9.70 cm water (-0.95kPa), and this at a peak flow of 354L(BTPS).min^{-1}. Similarly, at no time did the maximum pressure of expiration in the mask exceed +5.54 cm water (+0.54kPa). These findings compare most favourably with the pressure-flow curves established in the laboratory (Figures 3.1, p28 & 3.2, p29). Furthermore, the mean mask cavity pressure swing for the largest excursion in each sortie was only 7.87 cm water (0.77kPa).

Peak expiratory flows have not been recorded in flight, although expired gas has been collected, despite the fact that added expiratory resistance contributes as much as, if not more than, added inspiratory resistance to the total added load in modern military breathing systems, under both steady-state and dynamic conditions, (Figures 3.1, p28 & 3.3, p29).

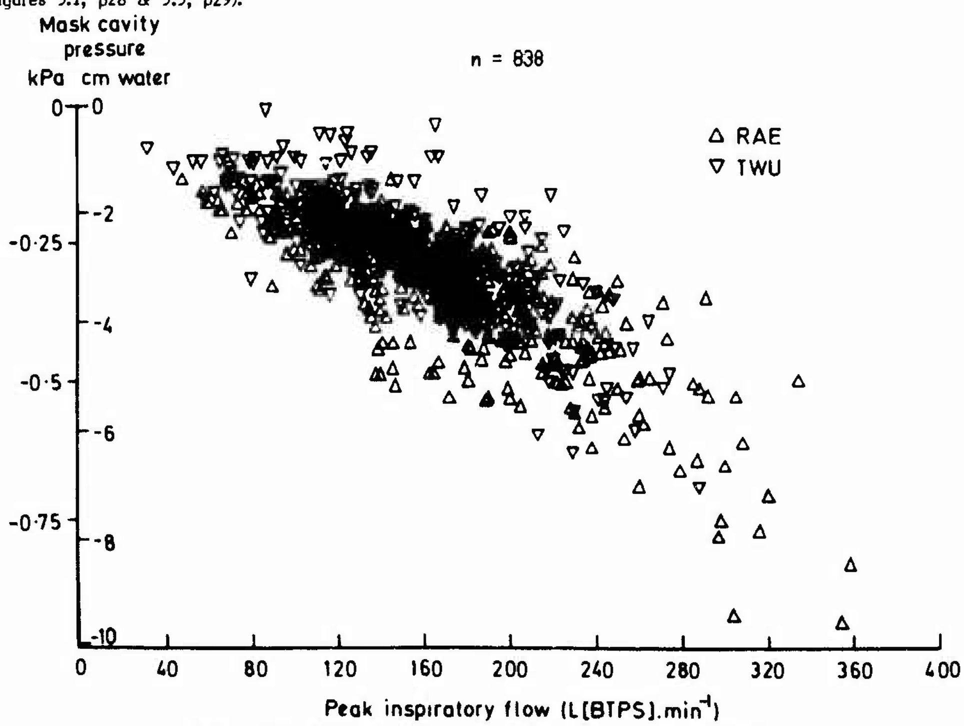


Figure 4.7 Relationship between mask cavity pressure and peak inspiratory flow
(Data derived from minimum pressure level observed during each minute of all MCP sorties and the corresponding peak inspiratory flow)

The findings of the present study may be compared with those of Silverman et al [44], whose extensive investigation of the effects of added external resistance on respiratory behaviour was referred to above and in Part 1, (p9). The total resistance of their basic system, with no added load, was only -0.30 to +0.73 cm water (-0.03 to +0.07kPa) at a flow of 200L.min^{-1}. To this system were added various inspiratory resistances of known magnitudes at flows of 85L.min^{-1}. The LRBS, with an inspiratory resistance of -1.7 cm water (-0.17kPa) at that flow, most closely approximates the Silverman system with a 2.5 cm water (0.24kPa) load. The mean values for respiratory frequency, minute volume and peak inspiratory flow for both systems are summarised at Table 4.3 for various work rates (sedentary, light, medium and heavy) in the case of the Silverman study, and for various flight phases in the case of the present study. This form of comparison, although not direct, does show that, as far as respiratory frequency and minute volume were concerned, the respiratory behaviour of subjects in flight lay between the sedentary and light classification of Silverman et al during routine phases and seven of the manoeuvring phases, and between the light and medium classification for six more manoeuvring phases. Only ACM and high G spirals could be classified between the medium and heavy loads. The results for peak inspiratory flow, however, are markedly different, and both maximum and mean peaks during all phases of the present study exceeded those reported by the Silverman group at all loads (apart from control levels). The reasons for this difference are not clear but it may be that both speech and special G-protective manoeuvres adopted by the pilots produced the very high peaks seen. No limitation on either was imposed and, although no attempt was made to correlate peak flows with speech, a positive correlation with +Gz manoeuvres was demonstrated and is illustrated at Figures 4.6b and 4.6c (p46). No mention of the relevance of speech was made in the Silverman study, although it has now been well-established that speech will influence both the shape and magnitude of the inspiratory phase. Thus, Ernsting, in 1960, concluded that speech imposed "some of the most severe demands upon breathing equipment .... which may be met in flight", by increasing both peak inspiratory flow and rate of change of flow, and decreasing the duration of inspiration.[125]

	Silverman et al[44] (2.5cm (0.24kPa) water resistance)					LRBS (1.7cm (0.17kPa) water resistance)					
	f	$\dot{V}_I$	$\bar{\dot{V}}_I$	$\bar{\dot{V}}_{I\,max}$	$\bar{\dot{V}}_I/\bar{\dot{V}}_{I\,max}$	f	$\dot{V}_I$	$\bar{\dot{V}}_I$	$\bar{\dot{V}}_{I\,max}$	$\bar{\dot{V}}_I/\bar{\dot{V}}_{I\,max}$	
	(.min^{-1})	(L(BTPS).min^{-1})			(as %)	(.min^{-1})	(L(BTPS).min^{-1})			(as %)	
Load											**Phase**
Sedentary	14.7	9.1	23.5	32.4	72	11.3	9.9	37			Control
						19.1	17.2	84	146	57	All Routine
						18.2	18.2	84	136	62	Strapping-in
						19.0	18.7	81	139	58	Taxy (pre-)
						18.8	18.9	82	140	59	Take-off
						18.8	16.0	81	147	55	Climb
						18.5	15.7	84	154	54	Cruise
						19.4	16.1	85	148	57	Descent
						21.4	19.1	90	152	59	Circuits
						19.8	17.8	87	143	61	Land
						19.4	18.8	91	143	64	Taxy (post-)
						20.7	17.1	77	135	57	2G Turns
						20.7	18.9	95	160	59	Low Level
						20.0	17.6	78	138	57	Steep Turns
						22.4	19.1	80	141	57	3G Turns
						23.7	20.5	85	150	57	4G Turns
						24.4	21.2	97	161	60	High G Spirals
						21.4	21.3	98	167	59	Recovery
						22.8	21.4	93	163	59	All Manoeuvring
Light	21.2	22.1	49.2	72.7	68						
						24.0	23.3	100	172	58	Loops
						22.5	22.3	102	178	57	Rolls
						24.5	23.5	105	196	54	Aerobatics
						25.1	22.6	96	162	59	Level Turns
						25.0	24.6	109	181	60	Barrel Rolls
						23.8	22.6	87	140	62	Wind-up Turns
Medium	29.2	24.7	70.4	95.0	74						
						27.4	25.0	102	160	64	6G Spirals
						26.7	32.8	144	218	66	ACM
Heavy	22.0	45.3	90.6	120.7	75						

Table 4.3
Comparison between respiratory variables recorded while using two low resistance systems: the LRBS and that of Silverman et al[44]

4.1.3 End-tidal Carbon Dioxide Tension. The frequency distribution of $P_{ET}CO_2$ for all phases of all sorties is shown at Figure 4.8. The overall mean value was 38.5 mmHg (5.13kPa), and the mean control (resting) value was 39.2 mmHg (5.22kPa). As with the inspiratory flow data, the values for $P_{ET}CO_2$ were meaned over one minute periods and the results aligned with the corresponding minute-by-minute analysis. The un-weighted mean results of this alignment are listed at Table 4.4 and shown graphically at Figures 4.9a and b for all phases combined and routine vs manoeuvring phases, and for individual phases respectively. Once again, a difference existed between the mean results from routine and manoeuvring phases (39.6 cf 36.1 mmHg (5.28 cf 4.81kPa)) but the most marked results when compared with all others were those obtained just after entering the aircraft, ie during strapping-in, pre-flight taxying and take-off. The mean $P_{ET}CO_2$ during these phases was 42.5 mmHg (5.67kPa) and was the highest mean value observed. The mean values for other routine phases of flight were considerably lower, being 37.7 mmHg (5.02kPa) during climb and cruise, and 38.2 mmHg (5.10kPa) during descent, circuits, approach and landing, and post-flight taxying. Of the 15 manoeuvring phases, only low level flight produced a mean $P_{ET}CO_2$ (39.1 mmHg (5.22kPa)) approaching those seen during routine phases. The remaining phases produced mean carbon dioxide tensions inversely proportional to the magnitude and duration of applied +Gz acceleration. Thus, by this criterion, rolls were the least stressful, with a mean end-tidal level of 36.6 mmHg (4.88kPa), followed by a group comprising 2G and 3G turns, loops, aerobatics and ACM, with a mean of 36.0 mmHg (4.86kPa). Thereafter, a progressive decline in mean level occurred during barrel rolls, steep turns, 4G turns, level turns, 6G spirals, high G spirals and wind-up turns, in that order. The mean value for the last three listed was 33.1 mmHg (4.41kPa), although it must be emphasised that the number of observations in each manoeuvring phase was low. Finally, recovery from manoeuvring flight produced a mean $P_{ET}CO_2$ of 36.8 mmHg (4.90kPa).

Early Routine Phases			Manoeuvring Phases			Late Routine Phases		
	$P_{ET}CO_2$	n		$P_{ET}CO_2$	n		$P_{ET}CO_2$	n
Strapping-in	43.1	126	Low level	39.1	41	Descent	38.2	114
Taxy	41.7	112	Recovery	36.8	71	Circuits	38.8	65
Take-off	43.4	20	Rolls	36.6	28	Land	39.5	16
Climb	37.9	96	ACM	36.2	22	Taxy	37.0	42
Cruise	37.4	110	2G turns	36.1	37			
			Aerobatics	36.0	18			
			3G turns	35.9	33			
			Loops	35.8	22			
			Barrel rolls	35.3	7			
			Steep turns	35.0	8			
			4G turns	34.2	24			
			Level turns	33.9	15			
			6G spirals	33.5	16			
			High G spirals	33.1	9			
			Wind-up turns	30.2	2			
All	40.4	464	All	36.1	353	All	38.2	237

[Overall mean = 38.5 (GH1 = 38.7, GH2 = 38.8, SCM = 38.0, ACM = 38.5)]

Table 4.4 Mean End-tidal Carbon Dioxide Tensions (mmHg)

Carbon dioxide tensions during flight in high performance aircraft have not been studied in this detail before. The present study does not support the contention of some earlier workers, reviewed in Part 1 (p11 et seq), that hyperventilation (assessed as a fall in P_ECO_2 to either <20 mmHg (2.66kPa)[12] or <30 mmHg (4.0kPa)[13,14]) occurs frequently. Although P_ECO_2 is several mmHg less than $P_{ET}CO_2$, by virtue of the effect of dead-space, mean values of the latter of <30 mmHg (4.0kPa) were seen in only four subjects in the present study, and then only briefly during high G manoeuvres; and no values <20 mmHg (2.66kPa) were encountered at all.

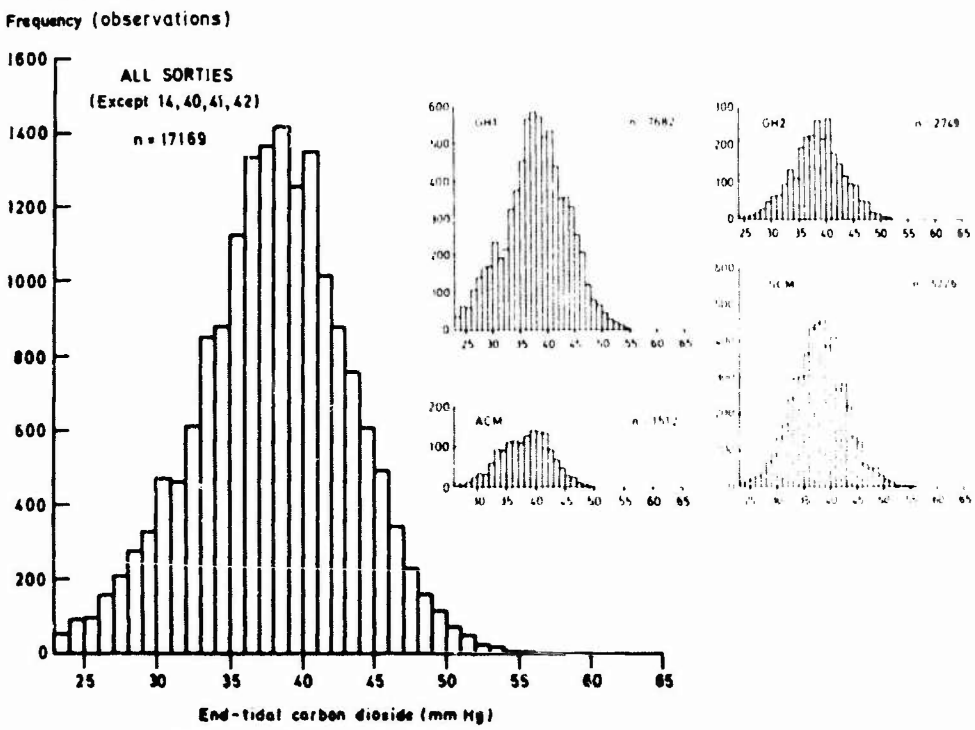


Figure 4.8 Frequency distribution for end-tidal carbon dioxide tensions all sorties combined
(Inset: frequency distributions for individual sortie types)

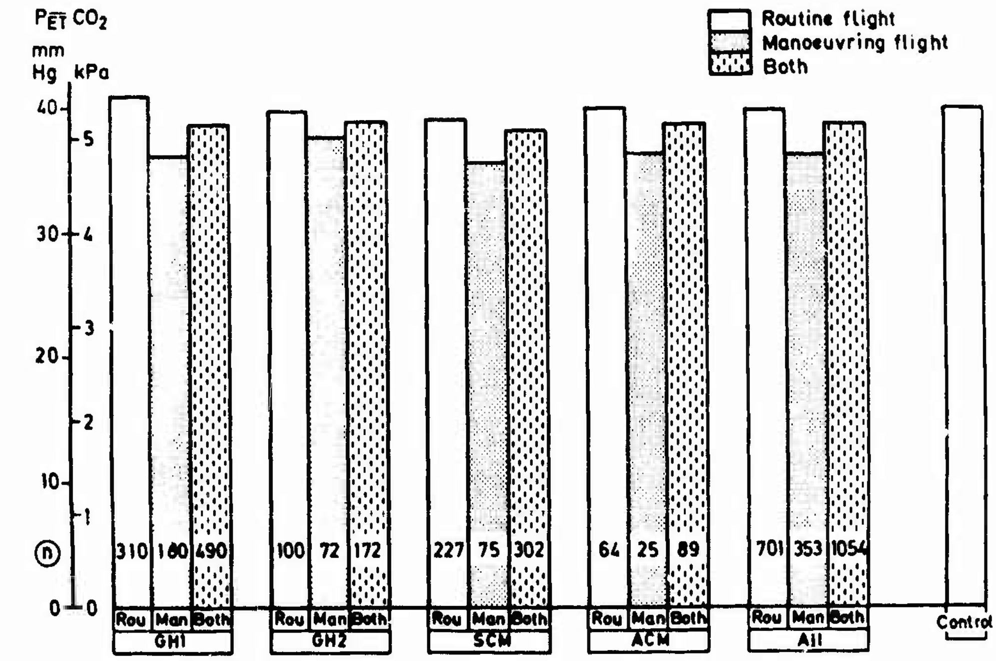


Figure 4.9a End-tidal Carbon Dioxide Tension
Un-weighted mean results of minute analysis: all phases combined and routine vs manoeuvring phases

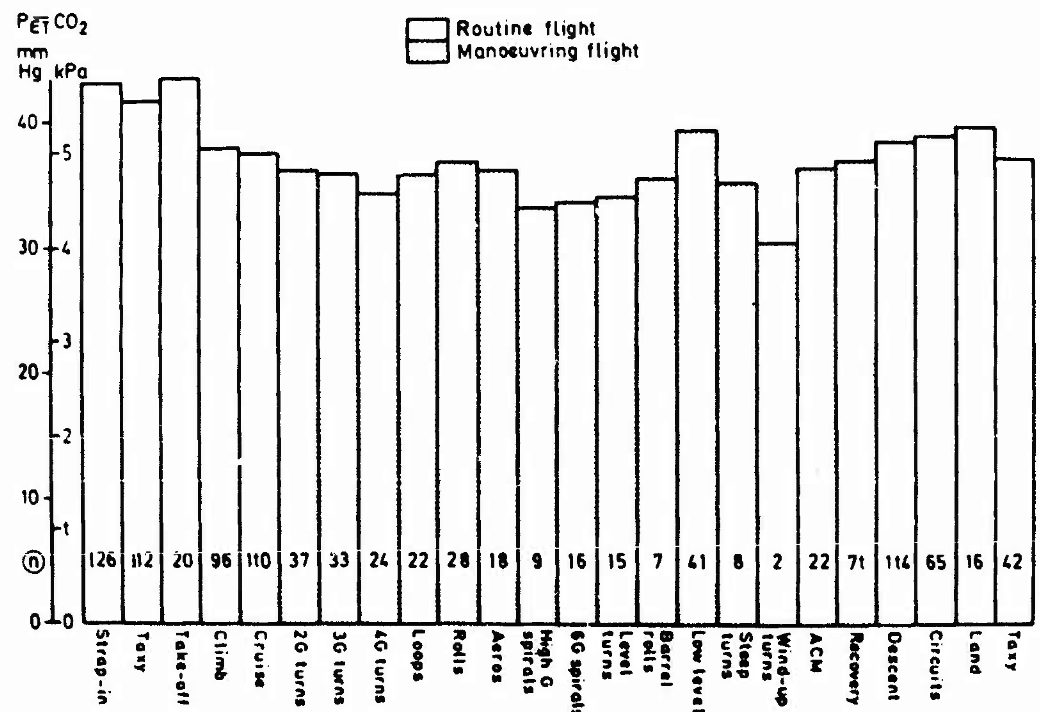


Figure 4.9b End-tidal Carbon Dioxide Tension
Un-weighted mean results of minute analysis: individual phases

On the other hand, there can be no doubt that manoeuvring flight produced a fall in $P_{ET}CO_2$ in all pilots studied, in all sortie types (Figure 4.9a); and, furthermore, that the fall was sustained. If hyperventilation is regarded as any fall in $P_{ET}CO_2$ from 'normal' as a result of increased pulmonary ventilation, then these pilots were hyperventilating, albeit mildly. This supports both the long-held suspicion that mild hyperventilation occurs during demanding flight[63], and the findings of Genin et al who concluded that mean end-tidal tensions fell by 5 mmHg (0.66kPa) in flight, with further falls at times of stress.[75] It contradicts the conclusion from the only other study of in-flight $P_{ET}CO_2$, by Murphy & Young[35], that hyperventilation does not occur, although this study was conducted in a light aircraft flying simple airfield circuits.

In view of the carbon dioxide tensions observed in the present study, it is not surprising that no overt symptoms or signs were reported by, or seen in, the subject pilots (cf p11). But the physiological consequences, if any, of the demonstrated prolonged low-grade hyperventilation are not clear, although it seems reasonable to suppose that cerebral function, and hence performance, would be compromised. This would only be the case, however, if the measured respiratory values for carbon dioxide tension reflected blood and tissue values. That this may not be so, at least during manoeuvring flight, is suggested by work on subjects in man-carrying centrifuges and is discussed below.

The apparent paradox of a declining end-tidal carbon dioxide tension at the same time as an increase in physical effort required to fly the aircraft may be explained on the basis of the means adopted by pilots to protect themselves against the cardiovascular consequences of sustained positive Gz acceleration, and of the local behaviour of the lungs during such acceleration. In the upright individual (ie with the G vector in the z axis), hydrostatic forces act upon the cardiovascular system such that the blood in the vessels between the heart and the brain exerts a pressure of about 25 mmHg (3.33kPa) under normal (+1Gz) conditions. Thus, a mean arterial pressure of 100 mmHg (13.33kPa), measured with reference to the level of the heart, is reduced to 75 mmHg (10.0kPa) at the brain. Positive Gz acceleration causes a pro rata rise in the hydrostatic pressure gradient and cerebral hypotension results. In the relaxed subject, the application of +Gz acceleration leads to impairment of visual function at about +3.5Gz and then to loss of consciousness at about +5.5Gz.[126] Modern high-performance combat aircraft are capable of sustaining flight at this, and indeed much higher, levels, and aircrew are obliged to utilise both passive and active methods to improve tolerance to +Gz acceleration.

One such passive method is the use of anti-g trousers which act, whenever +Gz acceleration is applied, by compressing the legs and lower abdomen so encouraging venous return and minimising peripheral pooling. The use of this garment increases tolerance by up to +1.5Gz, but its principal advantages are a reduction in transmural pressure because of mechanical support given to the arterial tree and a reduction in the fatigue which results from repeated high G manoeuvring. Anti-g trousers were worn by all subjects in the present study.

Active methods are also adopted by military aircrew to increase tolerance to +Gz acceleration. Panting, grunting, shouting and intermittent forced expiration against a partially closed glottis (M1 manoeuvre) are all used to raise intrathoracic pressure and so to facilitate venous return to the chest during the 'non-active' or relaxation phase of the manoeuvre. The increase in intra-thoracic pressure is transmitted directly to the arterial tree and so reduces cerebral hypotension. A combination of these procedures may increase tolerance by up to +2Gz. The M1 manoeuvre is the method of choice, however, particularly when combined with limb muscle straining.

All methods lead to hyperventilation (as defined above) despite the increased metabolic needs of the body during manoeuvring flight. It could be suggested, therefore, that the end-tidal carbon dioxide tensions seen in this study during manoeuvring phases of flight reflect a balance between increased metabolic needs of the body during such demanding activities and the hyperventilation induced by methods adopted by pilots to increase their tolerance to those activities. But this explanation is somewhat simplistic and neglects the marked disturbance in pulmonary gas exchange which occurs under +Gz acceleration as a result of ventilation-perfusion ($\dot{V}/\dot{Q}$) inequalities. The inverse relationship between $P_{ET}CO_2$ and degree of +Gz acceleration has been described before during studies using man-carrying centrifuges. One such study, in 1972, demonstrated a very marked fall in $P_{ET}CO_2$ from 33.6 mmHg (4.48kPa) at +1Gz to 27.3, 20.2 and 15.8 mmHg (3.64, 2.69 and 2.12kPa) after air breathing for 45 seconds at +3Gz, +5Gz and +8Gz respectively.[127] Concurrent analysis of blood gases revealed this decline to be a purely pulmonary manifestation, and specifically the result of increased physiological (alveolar) dead-space volume with increasing +Gz acceleration. Similarly, in 1973, Crossley et al found arterial carbon dioxide tensions to be independent of positive acceleration.[128] It is worth noting that a decrease in arterial oxygen tension with increasing +Gz acceleration was demonstrated in both studies and was attributed to the profound $\dot{V}/\dot{Q}$ inequalities which are known to develop within the lung when subjected to increased accelerations.[123]

The presence of perfused but un-ventilated alveoli in the lower regions of the lung at +3Gz acceleration was elegantly demonstrated by Glaister in 1965.[129] Radioactive Xenon-133 was injected systemically and so delivered to all perfused alveoli via the pulmonary circulation. Under +Gz acceleration, the slow rate of disappearance of activity from the lower lung fields closely matched that seen during breath-holding at +1Gz, so implying that alveoli, initially able to receive radioactivity and hence gas-containing, were losing activity back to the pulmonary circulation rather than through ventilatory wash-out; thus implying that some air trapping was taking place. This phenomenon partly explains the arterial hypoxaemia mentioned above. Conversely, $\dot{V}/\dot{Q}$ inequalities in the upper lung account for the fall in $P_{ET}CO_2$ seen under +Gz acceleration. In this case, well-ventilated but un-perfused alveoli contribute to the physiological dead-space so that alveolar carbon dioxide from the lower lung is continually diluted by relatively carbon dioxide-free gas coming from the un-perfused areas of the upper lung.[124]

Thus, the fall in $P_{ET}CO_2$ seen in the present study during manoeuvring flight is explicable in terms of the findings from previous ground-based work on centrifuges, and is the result of a combination of a true hyperventilation and the diluting effect of an increased physiological dead-space. It should be noted, however, that the increased ventilatory effort and the the effects of the $\dot{V}/\dot{Q}$ inequalities described are relevant only for as long as the lungs are subjected to increased acceleration. In the present study, the application of +Gz acceleration was never prolonged continuously beyond 1 - 1½ minutes and, although the dead-space effect may have been pronounced during these periods, there was ample time between each manoeuvre for recovery in this respect to occur. The magnitudes both of the diluting effect and that component of increased ventilation due solely to increased acceleration are not known, but it is suggested that they can only have exaggerated a pre-existing mild but true hyperventilation. That this was indeed the case is supported by the demonstration of a fall in $P_{ET}CO_2$ during the early +1Gz routine phases of flight. The aetiology of this prolonged low-grade hyperventilation must therefore involve some of the other factors discussed in Part 1 (p11 et seq). Hypoxia was unlikely to be of relevance, since the design of the LRBS was such as to prevent hypoxia occurring, and the other environmental causes, vibration and thermal stress, were also unlikely to have been of great influence. Similarly, pharmacological and pathological causes may be disregarded in this group of healthy pilots; and instrumental causes in the form of added external resistance had been minimised. Thus, covert psychological stress, as has always been suspected, must be regarded as the factor most likely to have induced the mild hyperventilation seen in the routine phases of the present study, with exaggerations in its magnitude at times of sustained acceleration being the result of physiological phenomena. These exaggerations are probably not accompanied by parallel falls in blood and tissue carbon dioxide tensions, and may be best described as episodes of 'specious' or false hyperventilation. It is likely, however, that the sustained fall in $P_{ET}CO_2$ does reflect a fall in blood and tissue levels and may have an effect, as yet undetermined, on performance.

The above discussion has taken no account of the influence of a sustained fall in carbon dioxide tensions upon body stores of the gas, although for a duration as here of 20 - 30 min there must have been some effect. Carbon dioxide stores are very large, amounting to about 20L in soft tissues and 100L in bone (relatively inaccessible), and are constantly readjusting slowly as a consequence of several physiological mechanisms, but particularly alveolar ventilation.[130] Since changes in body gas stores reflect the existence of an unsteady state, and as such mask the true level of metabolic carbon dioxide production, it is clearly desirable to establish the magnitude of the changes and the rate of re-equilibration. This was not attempted in this study and the phenomenon has been ignored; indeed, as argued below (p57), a steady-state was deemed to exist throughout. Notwithstanding this, the increased carbon dioxide elimination implied by the mild but prolonged hyperventilation described must have reflected a fall in carbon dioxide stores and, strictly, it would not have been possible to describe metabolic production until the steady-state was re-established. Quantifying the rate and degree of change in carbon dioxide stores, in order to determine when the steady-state is re-established, is important but difficult. This is because body tissues have different volumes, rates of perfusion, buffering capacities and solubilities, and so equilibrate at markedly different rates: alveolar gas and the pulmonary circulation within seconds/minutes, muscle and viscera within minutes/hours and bone over many days/weeks. Farhi has described a mathematical approach to changes in the alveolar-pulmonary compartment store as a result of changes in alveolar gas tension, and related to body weight and the solubility of the gas in these tissues.[131] Using his derivation here, the mean fall in the carbon dioxide content of that compartment, from take-off to the start of descent in 19 sorties, was 68 ml. Changes in the content of other compartments are even more difficult to compute and, in this study, would have required measurement of mixed venous carbon dioxide levels or of cardiac output. Without such knowledge, the total change in carbon dioxide stores cannot be determined and the implications of the fall cannot be considered.

Finally, the demonstration of elevated carbon dioxide tensions while strapping-in, during pre-flight taxying and on take-off is entirely in accord with the belief, founded on the results of ground-based studies such as those reviewed in Part 1 (p14), that the early phases of a military mission, while in the cockpit on the ground, are amongst the most expensive in terms of energy cost: a cost which is discussed below. It must also be noted, however, that some breath-holding occurs during the strapping-in process and this will also elevate $P_{ET}CO_2$.

<u>4.1.4 Metabolic Cost of Flying</u>. The energy cost of flying was derived from the recorded variables by invoking several assumptions, the validity of each of which is discussed below, p57 et seq. These assumptions were:

a. Steady-state conditions existed

b. No net exchange of nitrogen took place

c. Respiratory Exchange Ratio = 1

d. Caloric equivalent for oxygen = $5.047 kcal.L(STPD)O_2^{-1}$

e. $F_ICO_2 = 0$

f. $P_{ET}CO_2 = P_ACO_2$

g. Subject dead-space was constant, and mask dead-space = 150 ml

h. Inspired gas was dry

Now,

$$\dot{V}_{A(BTPS)} = (\dot{V}_{E(BTPS)} - \dot{V}_D) \qquad [5]$$

Then, from equation [2], and since R = 1,

$$\dot{V}_{I(BTPS)} = \dot{V}_{E(BTPS)} \qquad [6]$$

Therefore,

$$\dot{V}_{A(BTPS)} = (\dot{V}_{I(BTPS)} - \dot{V}_D) \qquad [7]$$

Where

$$\dot{V}_D = (V_{Ds} + V_{Dm}) \cdot f \qquad [8]$$

And since, by the law of partial pressures,

$$F_ACO_2 = \frac{P_ACO_2}{P_B - 47} \qquad [9]$$

and

$$\dot{V}CO_2 = F_ACO_2 \cdot \dot{V}_{A(BTPS)} \qquad [10]$$

Substituting equations [7] and [9] into equation [10],

$$\dot{V}CO_{2(BTPS)} = \frac{P_ACO_2}{P_B - 47} \cdot (\dot{V}_{I(BTPS)} - \dot{V}_D) \qquad [11]$$

and

$$\dot{V}CO_{2(STPD)} = \dot{V}CO_{2(BTPS)} \cdot \frac{273}{273 + 37} \cdot \frac{P_B - 47}{760} \qquad [12]$$

Then, since R = 1,

$$\dot{V}CO_{2(STPD)} = \dot{V}O_{2(STPD)} \qquad [13]$$

and so,

$$\text{Energy Expenditure} = \frac{\dot{V}O_{2(STPD)} \times 60 \times 5.047}{SA} \ \text{kcal.m}^{-2}.\text{h}^{-1} \qquad [14]$$

Thus, the corrected values for in-flight end-tidal carbon dioxide tension and inspiratory minute volume, together with the empirically determined anatomical dead-space (Table 2.1, p24), were used to derive alveolar ventilation, carbon dioxide production and thence energy expenditure.

The frequency distribution of energy expenditure so calculated for all phases of all sorties is shown at Figure 4.10. The overall mean was 85.2kcal.m^{-2}.h^{-1}, representing an increase of ~106% over the mean control (resting) value of 41.3kcal.m^{-2}.h^{-1} for this group (cf the mean resting value of 47.6kcal.m^{-2}.h^{-1} derived from the previous in-flight studies listed at Table 1.3, p13); and an increase of ~120% over its mean predicted 'standard' metabolic rate of 38.8kcal.m^{-2}.h^{-1} (Table 2.1, p24). The overall means for routine and manoeuvring flight were 82.9 and 89.8kcal.m^{-2}.h^{-1} respectively, but the close proximity of these values hides a marked difference between the individual phases studied. ACM, low level flight and rolls produced mean energy expenditures of 160.5, 121.2 and 101.3kcal.m^{-2}.h^{-1} respectively, while wind-up turns and steep turns (albeit with very few data points (n = 10)) produced a mean value of 57.9kcal.m^{-2}.h^{-1}. All other manoeuvring phases, and most routine phases, produced mean energy expenditure levels between these two extremes. Of particular interest, however, were the results from the early, routine, phases of strapping-in, taxying and take-off which yielded mean levels of 96.8, 93.5 and 107.6kcal.m^{-2}.h^{-1} respectively. The mean results are shown graphically at Figure 4.11a for all phases combined and routine vs manoeuvring phases, and at Figure 4.11b for individual phases. Numerical values are listed at Table 4.5 together with some comparative values from the literature for the energy cost of several everyday activities.

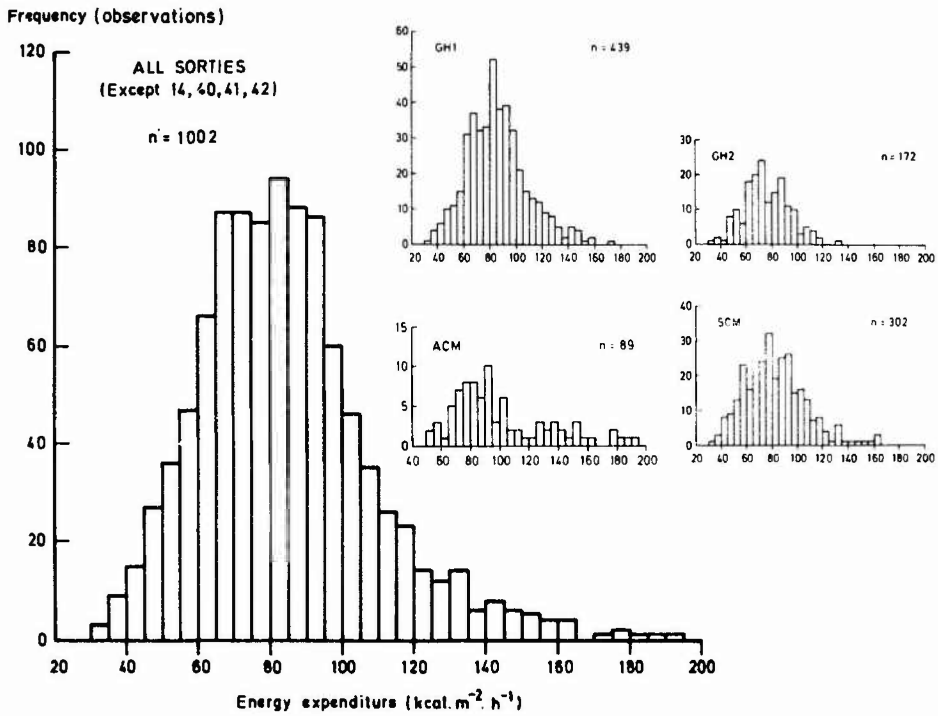


Figure 4.10 Frequency distribution for metabolic cost of flying: all sorties combined
(inset: frequency distribution for individual sortie types)

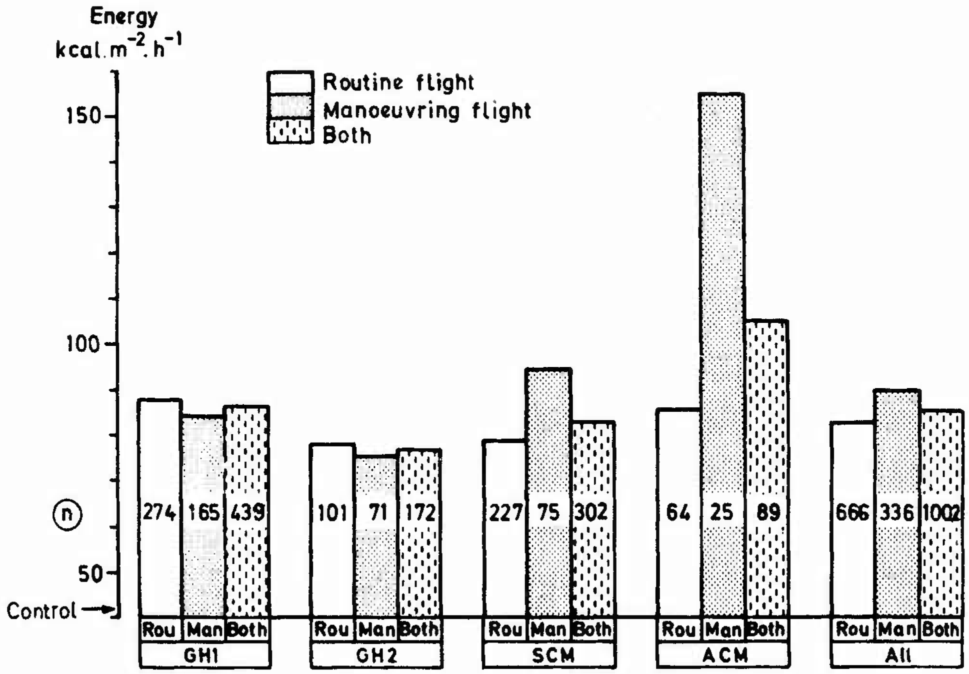


Figure 4.11a Metabolic Cost of Flying
Un-weighted mean results of minute analysis: all phases combined and routine vs manoeuvring phases

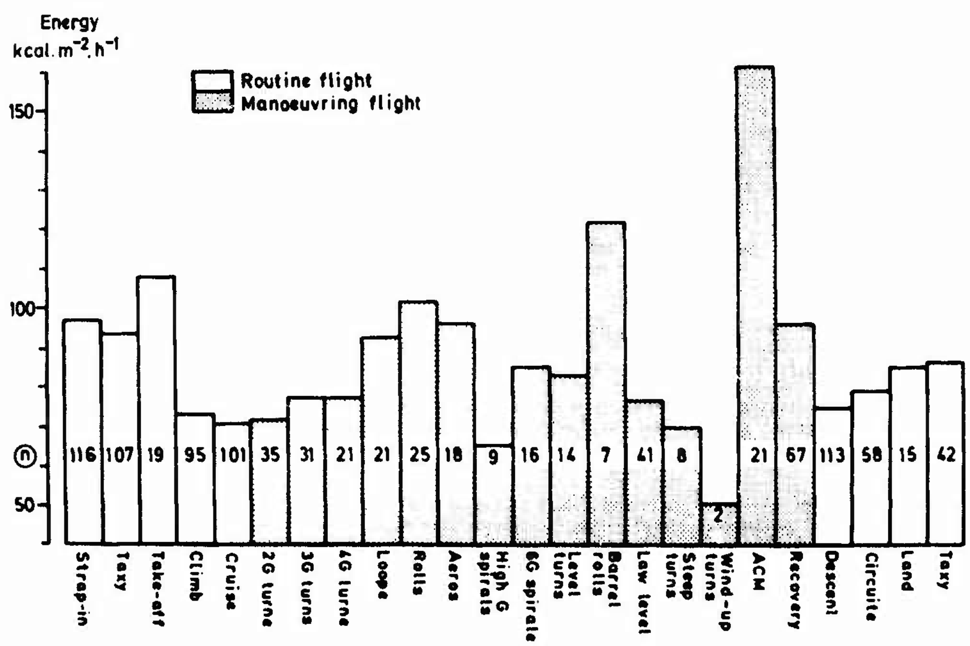


Figure 4.11b Metabolic Cost of Flying
Un-weighted mean results of minute analysis: individual phases

Flight Phase	VO_2 (ml(STPD) $.min^{-1}$)	Energy Expenditure ($kcal.m^{-2}.h^{-1}$)	n	Ground-based Activity*	Ref
All	536	85.22	1002		
Routine	522	82.9	666		
Manoeuvring	563	89.8	336		
Strapping-in	611	96.8	116		
Taxy (pre)	589	93.5	107		
Take-off	679	107.6	19		
Climb	463	73.0	95		
Cruise	445	70.8	101		
2G turns	449	71.6	35		
3G turns	483	77.1	31		
4G turns	479	77.1	21		
Loops	583	92.5	21		
Rolls	634	101.3	25		
Aerobatics	591	95.8	18		
High G spirals	419	65.0	9		
6G spirals	538	85.0	16		
Level turns	518	82.8	14		
Barrel rolls	760	121.2	7		
Low level	477	76.5	41		
Steep turns	372	59.8	8		
Wind-up turns	338	50.4	2		
ACM	1003	160.5	21		
Recovery	605	95.8	67		
Descent	472	74.6	113		
Circuits	484	78.5	58		
Land	532	84.3	15		
Taxy (post)	535	85.8	42		
		43.00		Sitting normally	
		51.00		Sitting, playing cards	
		86.70		Standing, light activity	
		86.70		Washing & dressing	129
		93.30		Driving a car	
		123.30		Cleaning windows	
		162.00		Mopping floors	
		60.0 - 93.3		Driving, standing, light engineering	
		76.7 - 140.0		Dressing, walking slowly, medium engineering	113
		120.0 - 173.3		polishing, walking normally, bricklaying	

* Published figures in kcal.min converted to $kcal.m^{-2}.h^{-1}$ by multiplying by 33.333 (assuming SA of $1.8m^2$) [$W.m^{-2} = kcal.m^{-2}.h^{-1} \times 1.1637$]

Table 4.5 The metabolic cost of flying compared with that of various ground-based activities

The energy cost of most flying can be seen to be similar to that of light to medium ground-based activities. Thus, energy expenditure during all routine phases of flight approximated to light activity while standing (eg washing and dressing), as assessed by Consolezio (quoted by Brobeck [129]), while expenditure during combined manoeuvring phases approximated that of driving a car. Of the more 'expensive' individual manoeuvring phases, low level flying approximated to cleaning windows, while ACM equated with mopping floors. Similarly, flying equated with a group of activities graduating from dressing, walking slowly and medium engineering to polishing, walking normally and bricklaying, as assessed by Cotes.[113] These more recent studies were in broad agreement with the classic review findings of Durnin and Passmore in 1955.[74]

When compared with previously published values for energy expenditure in flight (Table 1.3, p13), the values reported here were consistently higher during all phases considered, and for all aircraft types. The differences are not marked, however, and were probably caused by the different assumptions made in the various methods of calculation. It is important to note that direct measurement of energy expenditure in high performance fixed-wing aircraft has only been attempted once before, by Lorentzen nearly 20 years ago, and he too reported relatively high levels during aerobatic flight.[98] Indeed, notwithstanding the criticisms of his work (p14), the Lorentzen mean value of $98kcal.m^{-2}.h^{-1}$ correlates very well with the mean value of $95.8kcal.m^{-2}.h^{-1}$ reported here for the same phase. Furthermore, when compared, as above, with various ground-based activities, the levels of energy expenditure during all phases of the present study are intuitively more appropriate than previously published results, many of which equate with little more strenuous than sitting playing cards ($\sim 51kcal.m^{-2}.h^{-1}$).

At no time did energy expenditure in the present study approach the levels seen in the ground-based studies, discussed in Part 1 (p14), of the metabolic cost of dressing, walking and strapping-in while wearing various

AEAs, even though the summer AEA used in this study was very similar to that used before. Most particularly, the levels recorded while strapping-in do not correlate (96.82 cf 160kcal.m^{-2}.h^{-1}). While this again must be due in part to the different assumptions made and methods of calculation, other factors, such as speed of strapping-in, subject experience and environmental influences, must also have been relevant. In particular, in the earlier studies, a period of defined and controlled exercise, in the form of walking, preceded entry to the cockpit; whereas a short stroll of <50m from the crew-room to the aircraft preceded each flight in this series.

The necessity for the assumptions adopted for the above derivations is a reflection of the present limitations of in-flight physiological monitoring. It would clearly have been more desirable, and accurate, to measure oxygen uptake directly and/or expired gas volume and composition. But the lack of a suitable, fast-response, oxygen analyser prevented the former, while the mechanics of collection of expired gas would not only have been unacceptably bulky but also have compromised the requirement for a low resistance breathing system. There remains a need for a small but reliable respiratory gas analyser capable of operation in the environment of high performance flight. Until such a device is developed, assumptions such as those adopted here will be required for meaningful interpretation of available data. The reasoning behind each of the assumptions used in the present study was as follows:

a. Steady-state conditions existed. The respiratory 'steady state' is classically defined as a condition during which gas exchange with the atmosphere is constant.[131] As with all biological systems, such conditions for the respiratory system are virtually impossible to attain, although approximations can be made for short time intervals. Respiratory and exercise physiologists generally hold that a steady-state is established after five minutes of constant activity at the level under consideration.[133] It is quite clear, therefore, that steady-state conditions, as thus defined, could not have been achieved at any stage of the present in-flight study. Furthermore, the nature of high-performance military flying means that this will always be the case. The difficulty then arises of how to deal with data obtained during such flight. It was decided that steady-state conditions would be assumed to exist over the short periods (one minute) and very short periods (single breaths) analysed here, and that well-established mathematical considerations[134] could then be applied. The error involved in this assumption, in the face of continually changing subject and aircraft activity, is impossible to quantify; and it is suggested that it is conceptually valid not to attempt to do so. DuBois et al[135] have shown that only at two points during a single respiratory cycle do the alveolar partial pressures of oxygen and carbon dioxide correspond with their mean values: at about half way through both the inspiratory and expiratory phases. The correspondence is not synchronous, however, and even when steady-state conditions are said to exist measurements are subject to error. For example, readings taken too early in the expiratory phase will give a value for oxygen partial pressure which is too high, and a value for carbon dioxide partial pressure which is too low. The converse applies if sampling is left until late in the phase. Because of this continuous variation, even within a single respiratory cycle, it is suggested that a true steady-state can never be monitored or assessed with absolute accuracy and that the application of steady-state equations, as here, to single respiratory cycles or to several cycles combined, is as valid an approximation as is likely to be achieved in a dynamic experimental situation. Some support for this contention comes from Otis who, when talking of steady-state equations, has commented that (they) " ... are meaningful only if at least a complete respiratory cycle is considered ..." [134]

b. No net exchange of nitrogen took place. Leading respiratory physiologists have long held that, in the steady-state, whether at rest or during exercise, there is no net exchange of nitrogen between the atmosphere and the tissues since nitrogen is neither consumed nor produced by the body.[131, 134, 136] Indeed, many of the equations used to describe respiratory gas exchange are based upon this tenet.[136] But work in the 1960s and early 1970s, for example by Cissik et al[137], suggested that nitrogen retention or production could occur to a significant degree in steady-state conditions at rest and during exercise; and could produce considerable errors in subsequent determination of oxygen consumption. Farhi[138] has rebutted the interpretation of some of these data and, of particular relevance to the present study, Wilmore and Costill, in 1973, clearly demonstrated that while there may be some small production or retention of nitrogen during moderate steady-state exercise, this has little effect on the calculation of oxygen consumption using steady-state equations.[139] It may therefore be assumed that there is no significant exchange of nitrogen under steady-state conditions at ground level.

Ascent to altitude, however, will be associated with a fall in atmospheric pressure and a proportional fall in the partial pressures of constituent gases. Thus, in flight, the partial pressure of nitrogen in the inspired and expired gas will be fluctuating along with those of oxygen and carbon dioxide. A fall in the partial pressure of inspired nitrogen, as occurs during ascents, will disturb the normal equilibrium and tissue nitrogen tensions will also fall. Descents will have the opposite effect. The timescale of nitrogen washout from its principal tissue store, body fat, is so long, however, that body stores will not be affected for many minutes and not fully depleted for several hours, even when breathing 100% oxygen[131], although pulmonary washout is virtually complete within 20 breaths.[138] The breathing gas delivered by the LRBS was relatively rich in oxygen (p30), but there was sufficient nitrogen present throughout to delay changes in tissue and pulmonary levels as a result of altitude changes, which were anyway not prolonged, even further. It was concluded that any effect of ambient pressure change on nitrogen balance could be neglected.

c. Respiratory Exchange Ratio = 1. The respiratory exchange ratio, R, is the ratio of the mass of carbon dioxide evolved in the lungs to the mass of oxygen absorbed by them over the same period; and, in the steady-state, represents and equals the respiratory quotient (ratio of the mass of carbon dioxide produced by a tissue to the mass of oxygen consumed by it over the same period) of the whole body. Under changing physiological conditions, the two ratios may not be equal and so R may not reflect true metabolic activity. Nevertheless, in the present study, it was necessary to provide a means of relating the only two measured variables - inspired minute volume and end-tidal carbon dioxide tension - capable of providing an indication of metabolic function. Carbon dioxide production could be derived directly from expired minute volume if the latter could be regarded as the same as inspired minute volume; a manipulation which an assumed R of 1 allowed. As far as the minute volumes themselves are concerned, such an approximation would lead to an over-estimate of expired volume of 1 - 2% at sea level[140], rising to only about double this at the maximum cabin altitude (20,000 feet (6,096m)) experienced in this study. In terms of STPD volumes, however, the difference remains constant at all altitudes, at approximately 50 ml(STPD) for a minute volume of $6L(BTPS).min^{-1}$.[140] Conversely, the use of R = 1 would produce an under-estimate of oxygen consumption if standard basal conditions obtained. Under such conditions, R is regarded as an indication of the activity of the body at rest, and is assumed to have a value of 0.82. Standard conditions clearly did not exist in the present study and R would have been modified by many factors, including age, body build, previous diet and recent food intake, discomfort, noise and temperature etc.[115] But, most importantly, the value of R is increased by both hyperventilation and muscular activity[141]; and indeed both may cause R to exceed 1.[140,115] The relevance of these two features to the present study has already been demonstrated and it is concluded, therefore, that the use here of a respiratory exchange ratio of unity was reasonable and appropriate. A 10% over-estimation of the true value for oxygen consumption would result if R was 0.9 and a 10% under-estimation if R was 1.1: the most likely range to have been encountered.

d. Caloric Equivalent for Oxygen = $5.047kcal.L(STPD)O_2^{-1}$. The caloric equivalent for oxygen at a respiratory exchange ratio of one has been calculated as $5.047kcal.L(STPD)O_2^{-1}$, and this conversion factor was used in the present computations.[115] The equivalent chosen actually makes little difference to the final result: for example, a caloric equivalent of $4.825kcal.L(STPD)O_2^{-1}$ (the correct factor for a value of R = 0.82) would yield results for an R of 1 only 4.6% less than those obtained when the higher factor is used.

e. Partial pressure of inspired carbon dioxide = 0. Although carbon dioxide comprises 0.0314% by volume of dry air[142], its partial pressure in the inspired gas was assumed to be zero in the present study.

f. End-tidal carbon dioxide tension = alveolar carbon dioxide tension. The rationale behind equating the partial pressures of end-tidal gases with those of gases in the alveoli has long been recognised; the original method for collection of end-tidal samples being described by Haldane and Priestley in 1905.[143] This classic method, in which the gas at the end of a forced expiration is discretely sampled and analysed, does, however, lead to falsely high values for carbon dioxide tension and falsely low values for oxygen tension as a result of the effective breath-hold of the forced expiration and of the cross-over of mean values described above. The latter phenomenon also renders end-tidal sampling techniques, which aim to sample the last part of a normal expiration, prone to discrepancies. Continuous monitoring of one or more expired gases by mass spectrometry or, as here, by a single gas analyser allows the whole of each breath to be considered. Although it has been demonstrated that mean alveolar carbon dioxide tension is best represented by a sample taken shortly after the mid-expiratory point[115], a further correction is required to account for the timing error introduced by measurement at a site other than the lung. When transport time to the mouth was considered, Rahn and Farhi estimated the best sampling point to be about four-fifths of the time of expiration.[144] An even later point would be required to compensate for the time delay to the remote analyser employed in this study. Thus, it was considered that the errors introduced by measurement at the peak deflection of the carbon dioxide trace, instead of at a slightly earlier point, were sufficiently small to be disregarded, and that the peak deflection could be assumed to represent mean alveolar carbon dioxide tension.

Further support for this approach is provided by the results of studies in which end-tidal gas tensions were compared with directly measured blood gas tensions. Thus, Barker et al, in 1949, estimated alveolar gas tensions, by five different expiratory methods simultaneously, and found there to be agreement to within 2 mmHg (0.26kPa) of carbon dioxide tensions measured directly in arterial blood.[145] More recently, Jones et al (1966) have demonstrated that $P_{ET}CO_2 - P_aCO_2$ is virtually zero at rest, rising to only 1.2 mmHg (0.16kPa) during moderate exercise.[146]

g. Subject dead-space remained constant, and mask dead-space = 150 ml. The total or physiological dead-space is that volume of each breath delivered to the respiratory tract which does not participate in gas exchange. It is the sum of two components, themselves termed the anatomical (or series) dead-space and the alveolar (or parallel) dead-space. The former is the volume of those parts of the respiratory tract which are consistently ventilated but not perfused, ie the conducting airways; while the latter comprises the volume of those alveoli which are ventilated but for which no perfusion is available when the remaining alveoli are being ventilated and perfused with a $\dot{V}/\dot{Q}$ ratio of one. Mean anatomical dead-space is usually quoted as ~ 150 ml in healthy young men[113], a figure based on casts of bronchial trees and from results of single-breath analyses. The volume is, however, affected by physical factors such as age, sex, height and weight. Relationships between these factors and anatomical dead-space are the basis for the empirical methods used to determine the latter, (Table 2.1, p24).[113,116,117] Equation [7] (p53) demonstrates that total dead-space volume, and changes thereof, will intimately affect alveolar ventilation and hence gas exchange. Accurate measurements of total dead-space, and particularly of the alveolar component, are, however, fraught with difficulties. Controversy has surrounded the principal problem of what constitutes alveolar gas since at least the early 1900s[147], and once again the variability in composition of alveolar gas in time and space, even within a single respiratory cycle, is the underlying problem. The principle behind most calculations of dead-space volume is the classic relationship, described by Bohr in 1891, which states that the total amount of any gas exhaled is the sum of that from the alveoli and that from the dead-space (assuming that gas concentrations in the latter are the same as inspired concentrations). For carbon dioxide, this relationship may be expressed by equation [15]:

$$V_D = \frac{F_ACO_2 - F_ECO_2}{F_ACO_2 - F_ICO_2} \cdot V_E \qquad [15]$$

The precise numerical values to be used for alveolar carbon dioxide gives rise to the debate.

Notwithstanding this difficulty, the relationship between dead-space volume and respiratory frequency, total lung volume and tidal volume are of particular relevance to the present work. Thus, physiological dead-space has been reported by Bouhuys to be unaffected by changes in **respiratory frequency** of between 5 and 80 breaths.min^{-1} during both rest and exercise.[147] On the other hand, anatomical dead-space increases alinearly with **total lung volume** as a consequence of increased airway calibre due to mechanical stretching, as will occur during exercise and during +Gz acceleration.[123] The increases are not great, however, and have been reported as ~ 2.5 - 3.5 ml per 100ml increase in lung volume during single-breath studies.[148] Alveolar dead-space is also increased by exercise, but to a lesser degree than the increase caused by +Gz acceleration as a result of the exaggerated $\dot{V}/\dot{Q}$ inequality discussed above, p51.[127] There are conflicting views on the magnitude of effect of **tidal volume** on dead-space. Certainly, the anatomical component is affected little, but most authors report an increase in total dead-space with a rise in tidal volume, when the latter is accomplished by hyperventilation, or during breathing at a constant or elevated carbon dioxide level.[136] Some authors have reported a constant dead-space:tidal volume ratio[147], while others have shown an increase in dead-space of only 185 ml for a rise in tidal volume to 3.3L and have claimed that this reflected the small alveolar component seen in healthy young men.[150] It is clear from these studies that a rise in physiological dead-space volume, with increasing total or tidal volume, is primarily the result of changing alveolar dead-space, itself a consequence of altered $\dot{V}/\dot{Q}$ distribution.

In the present study, use of the Bohr equation could only have been possible if mixed expired carbon dioxide levels had been recorded. In view of this, and because of the conflicting evidence on the magnitude of changes in total dead-space, and because there were no very great changes in recorded tidal volume (mean maximum tidal volume = 1.33L(BTPS)) during flight, it was decided to neglect the possible effects of in-flight events on dead-space. A high empirical value for anatomical dead-space (Table 2.1, p24) was assumed on the grounds that any change in total dead-space during flight would probably have been upwards. It was calculated that alveolar ventilation would have been under-estimated by ~ 8% if dead-space had itself been under-estimated by 50 ml; with approximately pro rata changes in the magnitude of the error for other under-estimates or over-estimates.

A water displacement method was used to measure the dead-space volumes of oro-nasal masks mounted on a dummy head. Volumes of 150 ml and 128 ml were established for the large and small version of masks respectively. Since most of the subjects wore the large size LRBS mask in this study, and although variations in mask dead-space volume are known to exist as a result of the size of facial features and of differing degrees of adjustment of the mask to the face, it was felt that a constant value of 150 ml was appropriate.

h. Inspired gas was dry. Gaseous oxygen supplied for human use in aircraft is required to be of a very high standard of purity, and to contain <5.0mg.m^{-3} water at 15°C and 760 mmHg (10.13kPa).[151] Such was the standard of oxygen supplied to the pilots in the present study and, although there may have been some water vapour present in the general atmosphere of the cockpit, it was felt that with the point of measurement so close to the oxygen source this would have had little influence; particularly since cabin conditioning systems in their own right are known to dehydrate the cockpit environment. The inspired gas at the point of flow measurement was therefore assumed to be dry.

The likely repercussions of the assumptions made on the variables derived are summarised at Table 4.6. A quantitative estimation of the final movement in derived values has not been attempted, although an overall trend is suggested. Most importantly, it can be seen that an over-estimation of energy consumption has probably occurred, but the orders of magnitude of the results obtained implies that the combined effect of the assumptions was not great.

Effect of Assumption on Derived Variable	Value of derived variable moves in direction shown as a result of the assumption made						
	$\dot{V}_E$	$\dot{V}_A$	$P_{ET}CO_2$	P_ACO_2	$\dot{V}CO_2$	$\dot{V}O_2$	Energy
Steady-state existed	n/a	n/a	↑↓	↑↓	↑↓	↑↓	↑↓
R = 1	↑↓	↑↓	n/a	n/a	↑↓	↑↓	↑↓
Caloric equivalent = 5.047	n/a	n/a	n/a	n/a	n/a	n/a	↑*
$P_{ET}CO_2 = P_ACO_2$	n/a	n/a	n/a	↑	↑	↑	↑
V_D constant	n/a	↑*	n/a	↑	↑	↑	↑
Overall trend	↑↓	↑	↑↓	↑	↑	↑	↑

[n/a = not affected or not applicable, * = principal effect]

Table 4.6
The effect of assumptions made on the values of derived variables

4.1.5 Respiratory Inter-relationships. The above description of changes in individual respiratory [illegible] was a recognised, logical and convenient approach to the presentation of data. Quite clearly, however, such variables should not just be considered in isolation since each will influence, and be influenced by, the others. Inter-relationships between respiratory responses are often used to demonstrate causes and effects, and to provide a further insight to respiratory behaviour.

The primary purpose of the respiratory apparatus is to support the process whereby sufficient oxygen for their needs may be delivered to body cells, and whereby most of the carbon dioxide formed by the cells is eliminated to the atmosphere. To this purpose may be attributed the alterations in the physiological variables reported here. Thus, an increase in energy needs, and hence oxygen needs, at the cellular level will be manifest as an increase in oxygen uptake (and a parallel increase in carbon dioxide output) itself achieved by a rise in minute ventilation, and more specifically in alveolar ventilation. Figure 4.12 shows the relationship between energy expenditure and alveolar ventilation seen in the present study for all phases of all sorties during which carbon dioxide tensions were measured. The relationship was shown, by regression, to be linear over the range of expenditures seen during flight, but may have been expected to plateau if the physiological maximum for pulmonary ventilation had been approached. No such limit was approached in flight. The increase in alveolar ventilation reflects a similar rise in total minute ventilation, and this relationship, which was also linear, is shown at Figure 4.13.

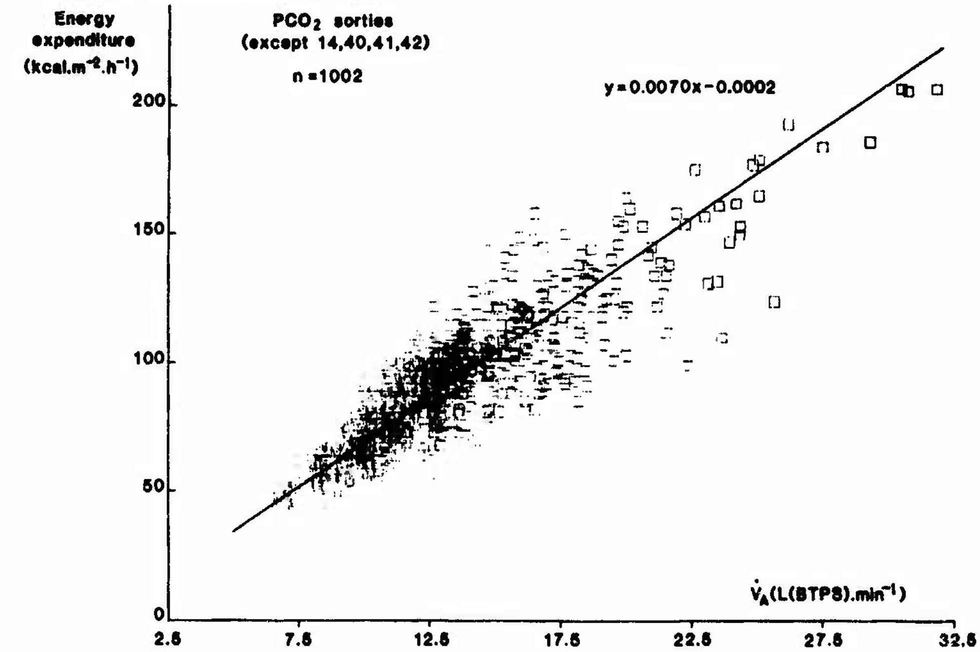


Figure 4.12
Relationship between energy expenditure and alveolar ventilation
(all phases combined)

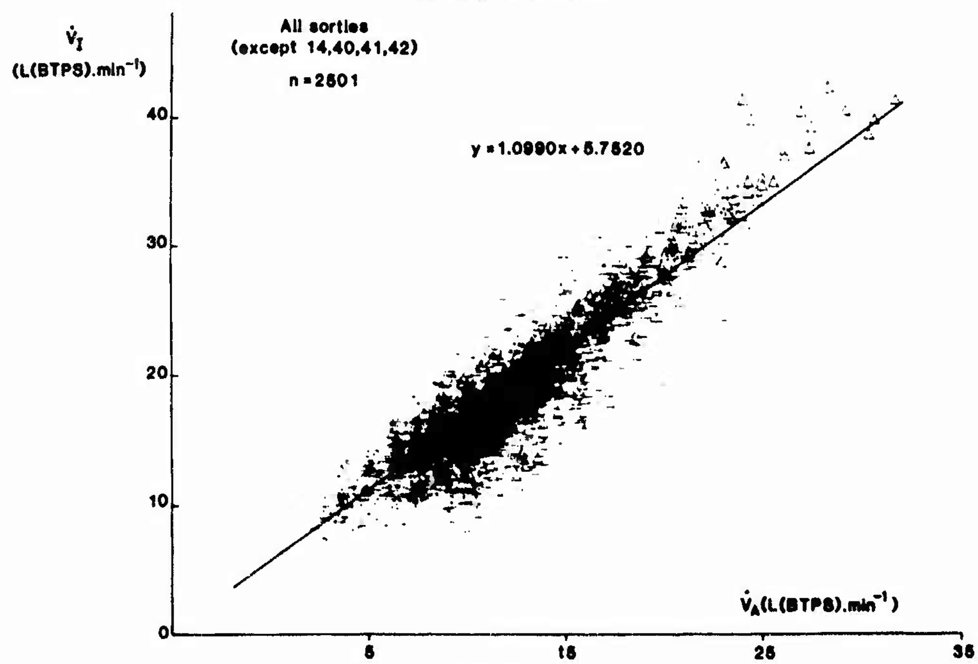
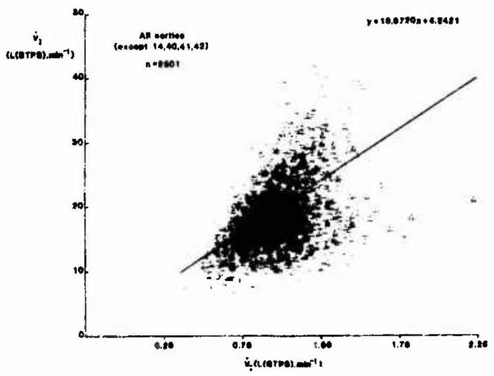


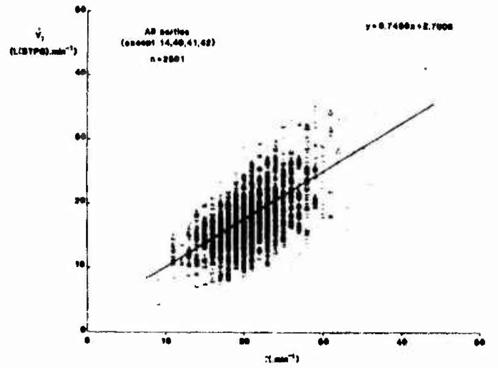
Figure 4.13
Relationship between alveolar ventilation and total minute ventilation
(all phases combined)

Increases in minute ventilation may themselves be achieved by an increase in respiratory frequency or an increase in respiratory depth (tidal volume) or by a combination of both. During light exercise at ground level, the increase in minute volume is primarily the result of an immediate rise in tidal volume; as the level of exercise increases, so there is an increasing contribution from an elevated respiratory frequency.[150] Figures 4.14a and 4.14b show respectively the effects of tidal volume and respiratory frequency on minute volume during flight. It can be seen that the slope of the former exceeds that of the latter (slope = 15.97 cf 0.74 respectively) so indicating that, for the relatively light exercise levels encountered, increased minute volume was, as in other situations, principally the consequence of increased tidal volume.

When the same data were plotted both for individual phases and for combined routine vs combined manoeuvring phases, no significant differences in the relationships were detectable so confirming the overall constancy of respiratory inter-relationships.



a. Relationship between tidal volume and minute volume



b. Relationship between respiratory frequency and minute volume

Figure 4.16
(all phases combined)

4.2 Summary

Respiratory frequency, inspired minute volume and peak inspiratory flow all varied directly with the degree of in-flight stress, as assessed in terms of applied acceleration. A clear difference was demonstrated between routine and manoeuvring phases of flight; and, of the various phases comprising the latter, air combat manoeuvring was the most demanding. Conversely, end-tidal carbon dioxide tension was at its greatest mean value just before and during take-off, so re-inforcing the belief that the early routine stages of a military flight are the most demanding, in terms of energy needs, as a consequence of dressing, walking or running to the aircraft and strapping into the seat. This was confirmed by a translation of the carbon dioxide and minute volume data, using several assumptions, to a measure of energy expenditure. This was relatively low during most phases of flight and highest, with the exception of air combat manoeuvring, low level flight and rolls, during the early post-entry stages in the cockpit. The pattern of end-tidal carbon dioxide tensions throughout the whole of each flight revealed an overall downward trend indicative of mild hyperventilation, so lending support to another long-held suspicion.

Part 5 - GENERAL DISCUSSION AND CONCLUSIONS

The study of physiology outside the controlled conditions of a laboratory has always been a challenge, and in-flight investigation is a supreme example of this. Similarly, the study of physiology during physical activity of any kind, but especially within confined and potentially hostile areas, is also extremely difficult. The cockpit of a military combat aircraft embraces both of these obstacles to successful experimentation and more, since the unique need for operational effectiveness, combined with acceptable levels of safety, precludes the use of the more adventurous techniques available to most investigators. Nevertheless, this study has shown that it is possible to record, accurately and reliably, various indices of respiration almost routinely during high performance flight, albeit in a dedicated research aircraft. This has only been possible because technology has advanced to the point where acceptable methods exist to measure and record those indices accurately with equipment sufficiently small to be accommodated, yet sufficiently sophisticated to be independent of the continually changing environment of flight. The small, sensitive pressure transducers, responsive and un-distorted during the application of high sustained accelerations, the infra-red carbon dioxide analyser based on a similarly responsive mechanism and the likewise robust high-fidelity on-board magnetic tape recorder were just three of the modern instruments essential to the success of this study.

The results have shown that, by using a breathing system of low added external resistance to avoid influencing respiratory behaviour, respiratory responses during various phases of flight were largely as might be predicted. Values for respiratory frequency, minute volume and peak inspiratory flow were significantly increased during all phases of routine flight, with further marked elevations during manoeuvring flight. No minute volumes in excess of the standards presently required of aircraft breathing systems by Western air forces were recorded, but peak inspiratory flows of the magnitude seen in this study clearly outstrip both the standards themselves and the systems striving to attain them. The significance of this shortfall, with 7.45% of all peaks >150L(BTPS).min^{-1} and 1.4% >200L(BTPS).min^{-1}, is not immediately apparent, but it seems likely that if naturally occurring physiological needs are not being met there may be a detrimental effect. The words of Nunnely and James in 1977, already quoted, are most appropriate here and bear repetition: "In the future, physiological conditions ... traditionally regarded as ... innocuous, may actually limit total system effectiveness". [**]

The same sentiment may be read across to the demonstration and possible significance of hyperventilation, although very mild, throughout a 20 - 30 minute flight. Studies of performance decrement as a consequence of hyperventilation have tended to confine themselves to the effects of more profound hyperventilation, and of shorter duration, than that observed here. But any effect on performance will be adverse and may become of immense importance at times of high cockpit stress, perhaps during emergencies or in combat.

Notwithstanding the assumptions necessary in this study to compute metabolic results from the recorded variables, the finding that high performance flying has a relatively low cost, in terms of energy expenditure, was expected in view of previously published work. It would indicate that flying an aircraft, although seemingly strenuous, in fact makes little energy demand on the body; probably as a direct consequence of the sitting posture adopted (cf the high energy cost of <u>any</u> mobile upright activity). Accordingly, walking to the aircraft, having first dressed in bulky aircrew clothing, and the relatively high physical effort involved in entering the cockpit and strapping into the seat, was appropriately more expensive.

The application of sustained Gz acceleration also had a predictably clear and disruptive effect on respiratory function, most obviously manifest as a fall in end-tidal carbon dioxide tensions during such manoeuvres, and explicable in terms of altered ventilation/perfusion relationships as identified by studies in man-carrying centrifuges.

Other findings included that of the significant difference between RAE and TWU pilots in some variables, and particularly minute volumes during routine flight. The phenomenon is not readily explicable either in terms of obvious subject group or sortie differences, or of variation in experimental conditions. Even the cockpit temperature profiles, as reflected in the inspired gas temperature records, showed no consistent pattern although the RAE phase was flown during late autumn and the TWU phase during late summer. Of course, the cabin conditioning system was at all times controlled by the pilots to ensure comfort.

All the experimental equipment performed well. The on-board carbon dioxide analyser, although subject to electrical problems if power surges occurred, worked very well indeed and must be regarded as an important step forward in techniques of in-flight measurement. Likewise, the in-flight calibration unit provided invaluable corroboration of pre-flight and post-flight calibrations. The ultrasonic digitizer also proved to be a reliable, effective and time-saving tool, which allowed processing of very large quantities of data. The subsequent pictorial representation of whole sorties points the way to the possibility of highly detailed analysis of individual breaths. But the digitizer should perhaps be regarded as just a stepping-stone to on-line analysis of recorded data with direct and immediate analogue-to-digital conversion the ultimate aim.

What else of the future? The concept of a total physiological monitoring system for in-flight use has perhaps been brought a little nearer by this study, but the ideal system embodying complete cardio-respiratory data collection is still a long way off and must await yet further technological advances. There is no doubt that such a system would be of immense value for both basic and applied research, but until multi-gas recording is possible, combined with continuous measurement of heart rate and blood pressure, enlargement of the data base will be limited to the variables studied here. Applied physiology, for example the effects of drugs such as -blockers upon cardio-respiratory function in flight, is of vital importance to the aviation world but its study, too, will be obliged to wait. A method for the non-invasive measurement of blood pressure is particularly vital, and all possible avenues require exploration; for example, the combined use of doppler ultrasound and pulse wave velocimetry.

In the short term, however, much further useful work, employing the techniques used here, could be directed towards establishing the respiratory behaviour of pilots before and during flight, for example while wearing chemical defence clothing; with complimentary laboratory studies of breathing flow patterns at rest and during exercise, both with and without speech, at ground level and at simulated altitudes in a hypobaric chamber.

Part 6 - REFERENCES

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Part 7 - APPENDICES

7.1 Appendix A - Pilot Briefing Sheet for the LRBS and CO_2 Analyser

1. General. Thank you for taking part in this flight research programme. Experiments undertaken using the low resistance breathing system (LRBS) and the on-board CO_2 analyser are designed to further our knowledge of basic respiratory physiology and energy expenditure in pilots of high performance aircraft. Such knowledge will assist in the determination of the specifications of life-support systems in future aircraft.

2. Equipment. For these experiments the subject pilot will use the LRBS and not the standard Hunter aircraft oxygen system. The LRBS consists of a continuous flow of oxygen from the high pressure aircraft supply to a reservoir mounted on a 'shoe' positioned behind the port ejection seat. Delivery from the reservoir is via anti-kink hose routed on, and attached to, the left-hand side of the seat. The hose terminates at a connection for the special-to-task mask assembly. The mask assembly consists of a modified Type P/Q (Med) series mask. A wide-bore mask hose is connected to the conventional expiratory port of the faceplece but provides the inspiratory pathway. A non-return inspiratory valve is located in this port. Expiration is via two, identical, non-return valves located in the conventional inspiratory port and the anti-suffocation valve port. A mask tapping, to allow sampling for the CO_2 analyser, is mounted in the right-hand side of the mask.

It must be noted that the continuous flow LRBS will not provide safety pressure or pressure breathing facilities and that a good mask fit is ESSENTIAL. A good mask fit is also essential to the success of the study. The aircraft is limited to a maximum altitude of 35,000 feet when the system is in use. Note also that operation of the LRBS will be indicated in the cockpit by a continuously white doll's eye.

In the event of an oxygen system emergency, a high flow of oxygen is available via the LRBS. This flow is initiated by rotating the barometric by-pass valve mounted aft of the port console and is signalled in the cockpit by a red indicator light mounted below the 70 $lb.in^{-2}$ doll's eye on the instrument panel. The barometric valve will operate automatically if cabin altitude exceeds 25,000 feet but it will not reset when cabin altitude falls below this level. A further, independent, oxygen supply, from the standard Mk 7A emergency oxygen set, is available to the pilot via the mask-hose connector.

A control box for the CO_2 analyser is installed in place of the starboard gunsight. This box has a system ON/OFF switch positioned halfway down on the right-hand side. ON is selected by the switch in the up position and a red light-emitting diode will then indicate 28 volts supply on. The unit requires no more than 45 seconds to settle after switching on and a green ready light, below the switch, will illuminate after this time. The instrument is then sampling CO_2. The sample pump, housed in the sensor unit, will be operative when internal power is applied to the airborne tape recorder and it may be assumed that the pump is running whenever there is power to the tape recorder.

3. Flight Protocols. The format of each experimental flight will be planned from instructions issued to the captain on the basis of previous results. The subject pilots will fly the sorties wearing normal Hunter AEA, with the exception of the modified mask assembly. Prior to strapping-in, the 70 $lb.in^{-2}$ gaseous oxygen supply must be turned ON and the function of the emergency high flow oxygen system confirmed. The latter is achieved by turning ON the barometric by-pass valve and noting that the red indicator light functions. The by-pass valve must then be turned OFF. Strapping-in is in the normal manner but remember that the LRBS oxygen delivery hose is routed from the left of the seat. Once strapped in, confirm that the seat/aircraft break connections, on the left-hand side of the seat, are securely made. For these experiments there is no requirement to restrict speech or MI manoeuvres.

The pre-flight oxygen system checks may be summarised thus :

LRBS PRE-FLIGHT OXYGEN SYSTEM CHECKS

Before Strapping In

- Confirm 70 $lb.in^{-2}$ supply ON
- Barometric By-pass Valve ON
- Confirm high flow red indicator light ON
- Barometric By-pass valve OFF

After Strapping In

- Confirm Connections Made
- Confirm Contents Sufficient
- Confirm Supply Pressure Normal (70 $lb.in^{-2}$)
- Confirm 70 $lb.in^{-2}$ MI Continuous White

4. Emergency Procedures. When the LRBS is in use, the procedures to be adopted in the event of an oxygen system emergency are as follows:

PASS CONTROL TO SECOND PILOT

PRESSURIZATION

Pressurization Failure
Rapid descent to below 20,000 feet cabin altitude
Monitor oxygen contents

Fumes
High Oxygen Flow .... ON
Pressurization .... OFF
Rapid descent to below 20,000 feet cabin altitude
Monitor oxygen contents

OXYGEN

Hypoxia
Connections .... Made
Contents .... Sufficient
Supply Pressure .... Normal (70 $lb.in^{-2}$)
High Oxygen Flow .... ON
Monitor Oxygen Contents
If oxygen supply not restored
Emergency Oxygen .... Operate
DO NOT DISCONNECT MAIN OXYGEN
Descend to 10,000 feet cabin altitude or below

Suspected Contamination
Emergency Oxygen .... Operate
Disconnect Main Oxygen
Descend to 10,000 feet cabin altitude or below

Continuous Black MI
Connections .... Made
Contents .... Sufficient
Supply Pressure .... Normal
High Oxygen Flow .... ON
Descend to 10,000 feet cabin altitude or below

5. The endurance in minutes of the oxygen system for both pilots, during routine and emergency operation, at various stages of flight, is shown in the table :

	Contents Gauge			
Configuration	Full	3/4	1/2	1/4
LRBS at 7 $L.min^{-1}$ Mk 17 on Airmix + SP	196	147	98	49
LRBS at 40$L.min^{-1}$ Mk 17 on 100%*	47	35	23	11

(NB * Cabin Altitude of 14,000 feet assumed)

6. Reports Required. A log is required of tape index numbers at the following events :

a. Start of take-off roll.
b. Entry to straight and level flight.
c. Entry to 2, 3, 4 and 6G turns.
d. Entry to loops, rolls and spirals.
e. Change of flight level and start of next manoeuvre.
f. CO_2 calibrations during flight.
g. Any period of deviation from the trial sequence.

The log will be maintained by the second pilot (captain). When applicable, the use and effectiveness of any MI manoeuvres performed should be reported.

Finally, the magnetic tape recorder must be switched to STOP, even in flight, when the index display reaches 500.0. This will leave sufficient tape to accommodate the post-flight calibrations.

7.2 Appendix B - Typical Flight Profile Log

IAM FLIGHT TEST OPERATIONS SORTIE REPORT

PROJECT TITLE: LRB5/CO_2 - BRAWOY TRIAL

PROJECT NUMBER: 616/A/18/05

PROJECT OFFICER: Sqn Ldr Harding

SORTIE NUMBER: 25 DATE: 09 Aug

AIRCRAFT: Hunter T7 XL563 Subject Pilot: PJ Safety Pilot: MB

TAKEOFF TIME: 1030 SORTIE DURATION: .45

FLIGHT PROFILE:
Strap in, taxy, take off
Climb to FL350
6G descending spiral to FL200
Further 6G spiral to FL70
Loops, 6G level turns, hi G barrel rolls
6G descending spiral to 2000'
RTB
Surveillance Radar Approach

TAPE EVENT INDEX:

INDEX	EVENT
0600/1135	Strap in/start
1322	Taxy
1699	Take off
2616	Level FL350
2627	Cal
2740	4~~6~~G spiral
2827	Level FL200
2960	Cal
2965	6G spiral
3075	Level FL70
3111	Cal
3286	Loop 1
3300	Loop 2
3425	6G turn 1
3510	6G turn 2
3560	HI G barrel 1
3612	Hi G barrel 2
3692	6G spiral
3755	Level 2000'
3934	Cal
3930	RTB
4600	Radar Approach
4905	Land

7.3 Appendix C - Calibration Correlation Coefficients for variables recorded

Sortie	Temp	Cabin Altitude	PCO_2 (all)	Flow	Mask Pressure
1st Phase (RAE)					
01	0.9999	-0.9909	-	0.9976	-0.9993
02	0.9998	-0.9987	-	0.9993	-0.9999
03	0.9998	-0.9987	-	0.9991	-0.9997
04	0.9994	-0.9997	-	0.9993	-0.9998
05	0.9995	-0.9996	-	0.9996	-0.9993
06	0.9995	-0.9998	-	0.9997	-0.9957
07	0.9992	-0.9994	-	0.9993	-0.9992
08	0.9997	-0.9994	-	0.9995	-0.9986
09	0.9999	-0.9995	-	0.9997	-0.9993
10	0.9995	-0.9997	-	0.9987	-0.9996
11	0.9991	-0.9995	-	0.9997	-0.9997
12	0.9989	-0.9996	-	0.9987	-0.9994
2nd Phase (TWU)					
13	0.9999	-0.9997	0.9976	0.9999	-
14	0.9999	-0.9999	0.9984	0.9997	-
15	0.9999	-0.9999	0.9982	0.9996	-
16	0.9999	-0.9999	0.9991	0.9996	-
17	0.9999	-0.9999	0.9979	0.9989	-
18	0.9995	-0.9999	0.9952	0.9997	-
19	0.9998	-0.9998	0.9952	0.9988	-
20	0.9999	-0.9999	-	0.9995	-0.9997
21	0.9999	-0.9999	0.9982	0.9995	-
22	0.9999	-0.9991	0.9968	0.9993	-
23	0.9999	-0.9997	-	0.9998	-0.9993
24	0.9999	-0.9999	-	0.9997	-0.9997
25	0.9999	-0.9999	0.9981	0.9996	-
26	0.9999	-0.9998	0.9985	0.9597	-
27	0.9997	-0.9999	0.9966	0.9993	-
28	0.9999	-0.9998	0.9984	0.9976	-
29	0.9999	-0.9999	-	0.9997	-0.9999
30	0.9999	-0.9999	-	0.9995	-0.9995
31	0.9999	-0.9996	0.9974	0.9995	-
32	0.9999	-0.9999	-	0.9993	-0.9999
33	0.9999	-0.9999	-	0.9997	-0.9999
34	0.9999	-0.9998	-	0.9992	-0.9998
35	0.9998	-0.9999	0.9977	0.9996	-
36	0.9999	-0.9999	0.9979	0.9945	-
37	0.9997	-0.9998	0.9812	0.9996	-
38	0.9998	-0.9999	-	0.9995	-0.9954
39	0.9999	-0.9592	-	0.9997	-0.9956
40	0.9999	-0.9991	0.9836	0.9997	-
41	0.9999	-0.9991	0.9958	0.9993	-
42	0.9999	-0.9991	0.9888	0.9995	-
43	0.9999	-0.9999	-	0.9992	-0.9998
44	0.9999	-0.9999	0.9987	0.9999	-
45	0.9998	-0.9998	0.9943	0.9991	-
46	0.9999	-0.9999	0.9984	0.9991	-

7.4 Appendix D - Statistical Analysis

All of the data presented in Part 4 were derived from the raw values obtained during flight. In a study of this nature, however, some influence on the results must have been exerted by the variability of and between individual subjects, subject groups (RAE or TWU), sortie types and phases within sorties. A comprehensive, incomplete blocks, analysis of variance was therefore performed to assess the influence of these various factors on the overall results. The analysis was performed on the data as extracted manually minute-by-minute, and as extracted breath-by-breath by the digitizer with subsequent conversion to minute means. No correction was made for the the possible instrumental or measurement errors discussed above, p36.

Two analyses were conducted for all measured variables. The first was an investigation of variation in physiological measurements with sortie type, and was based on data meaned over each minute with a separate analysis for each individual phase. For this analysis, three influencing factors were identified: subject (S), subject group (T (RAE or TWU)) and sortie type (G). S was treated as a random effect while T and G were regarded as fixed. S was nested under T and crossed with G, although not all subjects flew all sortie types. Two models were examined:

a. the main effects of S, G and T, and the GT interaction.

b. the main effects of S, G and T, the GT interaction and the GS interaction (not applicable for those phases which contained only one minute of observation per sortie).

For both models, the analysis of variance consisted of three stages as described by Kendall and Stuart.[32] Initially the mean squares due to terms involving the random effects (S and GS) were estimated by least squares in the presence of fixed effects; GS being estimated in the presence of S, whereas S itself was estimated excluding GS. On the basis of a separate analysis of dummy data, the components of variance due to S and GS were calculated from the mean squares and were then used to construct a co-variance matrix for the raw data, negative components being truncated to zero. The fixed effects, including the general mean, were then calculated from a weighted least squares analysis based on the co-variance matrix. The estimates of all the fixed effects would be unbiased if the experimental design was balanced in a general way but, with the unbalanced analysis undertaken here, there was no proof that all the estimates of effects were completely unbiased.

The second analysis was an investigation of differences between phases, and was based on phase data meaned over each minute. Four factors were identified for this analysis: S was treated as a random effect as before, with G, T and, additionally, phase (P) as the fixed effects. S was nested under T and crossed with G and P. Two models were again examined:

c. The main effects S, G, T and P.

d. The main effects S, G, T and P, and the GT, GP and GS interactions.

Since all measurements of PCO_2 were from the second group (TWU), the terms involving differences between subject groups were discarded from analyses of this variable. Practical limitations on the number of degrees of freedom which could be attributed to terms fitted in the models precluded the inclusion of a PS interaction, so inducing a further possible bias in this test. Because of these strictures, and the neglect of a possible effect (PS on PCO_2), comments on differences between phases must be viewed with some caution, although the results do provide clear indications of where the differences lie even though statements regarding probabilities may be imprecise. There was evidence of some differential variance <u>within</u> the various phases on the basis of this analysis but, since the number of minutes in each phase varied considerably from sortie to sortie and from phase to phase, tests for differences <u>between</u> phases must be regarded as indicative rather than precise.

The full numerical results of the analysis of variance are listed below for all variables considered. The data (excluding those from sorties 14 and 40 - 42) were analysed for all sorties combined, and separately for those flights involving carbon dioxide measurement. Tables are presented for both analyses respectively. Tables A4.1 to A4.13 list mean values for all physiological variables for both trial groups (RAE and TWU) and all sortie types, based on the phase by phase analysis. Dashed (-) cells in the tables were empty in the original data. The entries in the column labelled 'Grand Mean' are the weighted means over those trial groups and sortie types present in the original data. The term 'Sigma Squared (σ^2) within Phase' is a measure of variation between minutes within each phase separately, while 'Sigma Squared between Subject' is a measure of variation between subjects. The quantity 'Error Ratio' is the ratio of variance between subjects within phase to the variance between minutes within phase. A high value signifies a high variability between subjects and suggests that either the minute concerned was well-defined (aligned) in terms of event, or that the pilots were handling the manoeuvre in different ways. Within phase differences will clearly be markedly affected by misalignment. It should be noted that σ^2 may be regarded as the square of the standard deviation.

Tables A4.14 and A4.15 list comparisons, using a multiple comparison procedure, between sortie types, within trial groups, for all sorties combined and CO_2 sorties respectively. Each sortie profile in these two tables is represented by a number (GH1 = 1, SCM = 2, GH2 = 3, ACM = 4) and these are listed in rank order in each cell. Tables A4.16 and A4.17 list comparisons between phases, with sortie type and trial, again for all sorties combined and CO_2 sorties respectively. In these two tables, each phase is represented by its usual number (as listed in Tables A4.1-13) and these, too, are listed in rank order in each cell. In all four tables of comparisons, where the numbers are written without annotation, no significant difference between sortie types (Tables A4.14 & 15) or phases (Tables A4.16 & 17) was detectable. Where a sub-set of numbers is marked with a bar, there was no significant difference between the conditions so marked. Where a difference was detected, its significance is stated.

Tables A4.18 and A4.19 list the results of the analysis of variance for tests of differences between trial groups, sortie types or phases, for each phase separately (using model b), while Table A4.20 lists probabilities and the significance of differences for all phases combined (using model d). Table A4.21 provides a summary of the probabilities and striking significance of differences for routine vs manoeuvring phases of flight, together with indications of the sources of variation. Where the apparent degrees of freedom did not support the accurate calculation of probability levels, a dash (-) is placed in the cell. The * values were derived by examination of published values; and, where the probability is given as 1.0, the associated hypothesis could not be tested.

The overall conclusion from the statistical analysis, particularly from Tables A4.18-21, is that the marked differences seen between the two subject groups (RAE and TWU), the four sortie profiles and the 24 phases within these sorties were as reported in Part 4 of this study.

Finally, the relationships between pairs of physiological variables (p59 et seq) were calculated in two stages. A regression was first calculated separately for each pair of variables in each sortie. The regression coefficients and intercepts were then investigated using the incomplete blocks analysis of variance (model a. being assumed in each case) and consolidated significant slopes and intercepts determined.

	Phase	GW1 (RAE)	GW1 (TWU)	SCM (RAE)	SCM (TWU)	GW2 (TWU)	ACM (TWU)	Grand Mean	Sigma Squared Within Phase	Error Ratio	Sigma Squared Between Subject
1	Strap-in	-	17.90	-	18.72	18.36	16.45	18.10	10.0816	0.3866	3.8975
2	Taxy (pre-flight)	20.19	19.63	19.85	19.36	19.55	18.05	19.40	5.7684	1.3808	7.9650
3	Take-off	18.33	19.56	19.17	18.21	19.16	17.16	18.80	6.0391	0.6578	3.9725
4	Climb	20.46	19.97	19.22	18.39	19.88	19.42	19.05	7.8306	1.1729	9.1845
5	Cruise	18.58	19.10	19.46	18.12	19.29	20.89	18.99	8.3234	0.9736	8.1036
6	2G Turns	20.75	21.18	-	-	-	-	21.03	5.3311	1.8347	9.7810
7	3G Turns	21.25	22.86	-	-	-	-	22.33	5.5975	1.9876	11.1256
8	4G Turns	22.61	24.21	-	-	-	-	23.59	3.6380	3.8012	13.8288
9	Loops	21.98	24.36	24.24	24.45	-	-	24.12	9.0000	1.0774	10.5585
10	Rolls	21.84	22.62	-	-	-	-	22.32	6.6434	0.7503	4.9846
11	Aerobatics	21.67	25.01	-	22.75	25.30	-	24.41	6.3036	2.2086	13.9222
12	High G Spirals	-	-	23.12	26.16	-	-	24.43	34.8148	0.0863	3.0045
13	6G Spirals	-	19.21	28.69	26.85	-	-	27.25	20.1609	0.8070	16.2698
14	Level Turns	-	24.81	25.23	26.21	23.02	-	25.20	6.7708	2.5960	17.5771
15	Barrel Rolls	-	-	24.55	25.58	-	-	25.13	4.3333	3.5191	15.2494
16	Low Level	-	-	-	-	19.78	-	19.78	5.8633	1.6733	9.5099
17	Steep Turns	-	-	-	-	18.24	-	18.24	1.1667	8.2939	9.6762
18	Wind-up Turns	-	-	-	-	23.60	-	23.60	8.5000	0.6782	5.7647
19	ACM	-	-	-	-	-	26.94	26.94	11.6245	0.1407	1.6356
20	Recovery	20.85	19.91	23.13	23.38	21.00	24.15	21.56	10.1215	0.7258	7.3462
21	Descent/RTB	18.39	19.54	21.11	20.96	19.80	17.94	19.73	8.6287	1.0904	9.4087
22	Circuits	-	20.63	22.80	20.82	20.46	-	20.95	3.8954	1.4404	5.6109
23	Land	21.67	19.73	18.67	20.49	18.85	19.80	20.01	11.2157	0.1874	2.1018
24	Taxy (post-flight)	19.53	19.77	19.38	20.36	18.18	15.89	19.31	5.1841	1.5118	7.8373

Table A4.1 Mean values for respiratory frequency - all sorties combined
[.min $^{-1}$]

	Phase	GW1 (RAE)	GW1 (TWU)	SCM (RAE)	SCM (TWU)	GW2 (TWU)	ACM (TWU)	Grand Mean	Sigma Squared Within Phase	Error Ratio	Sigma Squared Between Subject
1	Strap-in	-	17.92	-	17.86	18.25	15.83	17.73	10.8890	0.4009	4.3654
2	Taxy (pre-flight)	-	19.68	-	19.50	19.61	17.54	19.28	5.8463	1.9279	11.2711
3	Take-off	-	19.36	-	17.54	18.12	16.84	18.32	7.4418	1.3122	9.7652
4	Climb	-	18.74	-	17.50	19.30	19.14	18.01	5.0789	2.7553	13.9940
5	Cruise	-	18.32	-	18.14	19.55	21.38	18.76	7.3928	0.7667	5.6680
6	2G Turns	-	19.85	-	-	-	-	19.85	5.3333	1.2173	6.4923
7	3G Turns	-	21.36	-	-	-	-	21.36	5.9942	1.6223	9.7244
8	4G Turns	-	23.51	-	-	-	-	23.51	2.0256	9.2759	18.7896
9	Loops	-	22.18	-	23.16	-	-	22.79	15.9286	0.2977	4.7419
10	Rolls	-	22.12	-	-	-	-	22.12	4.5020	1.0953	4.9310
11	Aerobatics	-	24.23	-	-	23.53	-	23.72	4.2679	6.0051	25.6289
12	High G Spirals	-	-	-	24.11	-	-	24.11	3.1250	0.0000	0.0000
13	6G Spirals	-	-	-	28.13	-	-	28.13	11.2000	2.5192	28.2150
14	Level Turns	-	25.00	-	25.59	20.35	-	23.81	9.4333	1.3598	12.8274
15	Barrel Rolls	-	-	-	26.37	-	-	26.37	12.5000	0.2560	3.2000
16	Low Level	-	-	-	-	18.02	-	18.02	3.8113	2.3709	9.0363
17	Steep Turns	-	-	-	-	17.62	-	17.62	0.6333	28.7219	18.1905
18	Wind-up Turns	-	-	-	-	22.50	-	22.50	12.5000	0.0000	0.0000
19	ACM	-	-	-	-	-	26.94	26.94	11.6245	0.1097	1.2752
20	Recovery	-	19.28	-	22.99	20.90	23.79	20.82	7.1867	0.4223	3.0349
21	Descent/RTB	-	19.22	-	21.20	18.50	17.43	19.51	5.4772	2.0632	11.3006
22	Circuits	-	20.38	-	20.53	19.00	-	20.21	3.1375	0.9228	2.8953
23	Land	-	19.43	-	20.07	19.43	20.30	19.80	2.9418	3.1736	9.3360
24	Taxy (post-flight)	-	19.13	-	19.71	18.59	15.70	18.81	3.9149	2.5826	10.1106

Table A4.2 Mean values for respiratory frequency - PCO_2 sorties
[.min $^{-1}$]

	Phase	GM1 (RAE)	GM1 (TWU)	SCM (RAE)	SCM (TWU)	GM2 (TWU)	ACM (TWU)	Grand Mean	Sigma Squared Within Phase	Error Ratio	Sigma Squared Between Subject
1	Strap-in	-	16.40	-	16.06	16.84	17.16	16.41	8.8767	0.5677	5.0393
2	Taxy (pre-flight)	16.26	16.96	15.22	17.56	18.40	16.98	17.31	4.5183	2.4999	11.0467
3	Take-off	14.82	18.49	15.52	17.39	19.46	21.60	17.54	6.7600	2.0279	13.7087
4	Climb	16.44	18.26	12.83	15.03	16.93	18.27	15.07	7.8351	1.2567	9.8464
5	Cruise	12.91	16.12	14.56	16.29	17.41	19.99	15.53	7.7553	1.2544	9.7283
6	2G Turns	15.17	16.99	-	-	-	-	16.36	4.7455	3.6718	17.4245
7	3G Turns	16.50	18.39	-	-	-	-	17.77	6.5624	3.3745	22.1447
8	4G Turns	19.01	20.10	-	-	-	-	19.67	5.0062	5.5074	27.5709
9	Loops	22.33	22.71	23.70	22.85	-	-	22.97	7.0805	2.3027	16.3042
10	Rolls	19.32	22.31	-	-	-	-	21.17	5.5539	5.2566	29.1948
11	Aerobatics	18.56	23.70	-	18.95	22.74	-	21.77	19.7099	0.6946	13.6905
12	High G Spirals	-	-	20.22	22.17	-	-	21.07	47.3051	0.0157	0.7427
13	6G Spirals	-	27.62	26.73	23.45	-	-	24.56	38.6350	0.3750	14.4881
14	Level Turns	-	22.50	22.36	22.82	17.05	-	21.49	4.6042	3.9470	18.1728
15	Barrel Rolls	-	-	23.16	26.61	-	-	25.11	5.7548	2.3440	13.4893
16	Low Level	-	-	-	-	17.28	-	17.28	8.1570	0.6504	5.3053
17	Steep Turns	-	-	-	-	15.54	-	15.54	2.1124	2.7580	5.8261
18	Wind-up Turns	-	-	-	-	20.56	-	20.56	24.5732	0.0000	0.0000
19	ACM	-	-	-	-	-	33.42	33.42	17.2117	0.1514	2.6059
20	Recovery	17.38	19.07	21.42	23.26	21.56	25.69	20.42	14.8795	1.2211	18.1694
21	Descent/RTB	11.66	15.84	14.80	17.24	17.26	16.79	15.33	5.7374	1.8346	10.5259
22	Circuits	-	15.96	16.18	20.86	20.05	-	18.30	5.0260	2.6946	13.5431
23	Land	15.49	19.63	13.61	19.27	20.01	20.00	17.94	8.0101	0.8112	6.4978
24	Taxy (post-flight)	12.64	19.70	16.27	18.18	17.07	18.95	18.11	5.4435	0.5771	3.1414

Table A4.3 Mean values for minute volume - all sorties combined
$[L(BTPS).min^{-1}]$

	Phase	GM1 (RAE)	GM1 (TWU)	SCM (RAE)	SCM (TWU)	GM2 (TWU)	ACM (TWU)	Grand Mean	Sigma Squared Within Phase	Error Ratio	Sigma Squared Between Subject
1	Strap-in	-	16.47	-	17.49	17.04	17.58	16.88	10.4894	0.1408	1.4769
2	Taxy (pre-flight)	-	17.24	-	18.26	18.91	17.39	17.79	4.1270	1.7058	7.0399
3	Take-off	-	18.46	-	18.18	19.12	21.70	18.82	7.0720	0.6580	4.6534
4	Climb	-	17.12	-	14.96	16.02	18.41	15.68	7.1284	0.3636	2.5919
5	Cruise	-	15.18	-	16.75	16.97	20.10	16.25	4.9338	1.6163	7.9745
6	2G Turns	-	15.67	-	-	-	-	15.67	5.0895	2.7933	14.2166
7	3G Turns	-	16.66	-	-	-	-	16.66	6.1361	4.1372	25.3861
8	4G Turns	-	18.33	-	-	-	-	18.33	3.9951	7.9543	31.7781
9	Loops	-	20.82	-	21.78	-	-	21.42	8.9775	1.4061	12.6232
10	Rolls	-	20.49	-	-	-	-	20.49	5.2325	7.8124	40.8786
11	Aerobatics	-	22.28	-	-	20.78	-	21.19	9.1989	0.0919	0.8454
12	High G Spirals	-	-	-	18.98	-	-	18.98	60.0331	0.0000	0.0000
13	6G Spirals	-	-	-	23.41	-	-	23.41	41.8337	0.0861	3.6019
14	Level Turns	-	23.22	-	21.98	15.44	-	19.88	8.6504	0.2416	2.0899
15	Barrel Rolls	-	-	-	27.44	-	-	27.44	6.0204	0.3099	1.8657
16	Low Level	-	-	-	-	15.68	-	15.68	2.9222	0.5122	1.4967
17	Steep Turns	-	-	-	-	14.28	-	14.28	1.4256	2.2141	3.1564
18	Wind-up Turns	-	-	-	-	16.05	-	16.05	0.0024	0.0000	0.0000
19	ACM	-	-	-	-	-	33.41	33.41	17.2117	0.3489	6.0052
20	Recovery	-	17.88	-	24.19	22.11	26.04	20.62	9.8266	1.7832	17.5228
21	Descent/RTB	-	15.44	-	18.12	16.68	17.08	16.75	4.3597	1.1802	5.1453
22	Circuits	-	14.59	-	19.07	18.30	-	16.40	2.9730	1.6941	5.0366
23	Land	-	17.63	-	18.53	17.83	18.84	18.18	3.4027	0.7425	2.5265
24	Taxy (post-flight)	-	18.98	-	18.66	17.05	19.23	18.55	4.0928	1.0259	4.1988

Table A4.4 Mean values for minute volume - PCO_2 sorties
$[L(BTPS).min^{-1}]$

	Phase	GN1 (RAE)	GN1 (TWU)	SCM (RAE)	SCM (TWU)	GN2 (TWU)	ACM (TWU)	Grand Mean	Sigma Squared Within Phase	Error Ratio	Sigma Squared Between Subject
1	Strap-in	-	1.08	-	0.96	0.97	1.12	1.04	0.0321	0.5676	0.0182
2	Taxy (pre-flight)	0.88	0.99	0.73	0.99	1.00	1.05	0.99	0.0248	0.5052	0.0125
3	Take-off	0.82	1.09	0.81	1.06	1.09	1.30	1.01	0.0167	1.3648	0.0228
4	Climb	0.81	1.02	0.68	0.91	0.90	1.01	0.85	0.0192	0.6101	0.0117
5	Cruise	0.69	0.95	0.72	0.95	0.94	0.99	0.85	0.0156	0.7130	0.0111
6	2G Turns	0.73	0.89	-	-	-	-	0.84	0.0131	0.7480	0.0098
7	3G Turns	0.78	0.90	-	-	-	-	0.86	0.0122	0.8201	0.0100
8	4G Turns	0.84	0.91	-	-	-	-	0.89	0.0072	3.7937	0.0275
9	Loops	0.99	1.02	0.99	0.96	-	-	0.99	0.0077	1.9309	0.0148
10	Rolls	0.90	1.06	-	-	-	-	1.00	0.0092	2.0709	0.0190
11	Aerobatics	0.87	1.03	-	0.89	0.95	-	0.94	0.0125	0.5891	0.0074
12	High G Spirals	-	-	0.87	0.87	-	-	0.87	0.0311	0.0000	0.0000
13	6G Spirals	-	1.35	0.92	0.90	-	-	0.92	0.0226	0.7107	0.0161
14	Level Turns	-	0.94	0.89	0.95	0.78	-	0.89	0.0089	0.3688	0.0033
15	Barrel Rolls	-	-	0.95	1.03	-	-	1.00	0.0037	3.4486	0.0127
16	Low Level	-	-	-	-	0.93	-	0.93	0.0194	0.9604	0.0186
17	Steep Turns	-	-	-	-	0.89	-	0.89	0.0065	1.8152	0.0118
18	Wind-up Turns	-	-	-	-	0.92	-	0.92	0.0194	0.1491	0.0029
19	ACM	-	-	-	-	-	1.23	1.23	0.0168	0.0000	0.0000
20	Recovery	0.85	1.05	0.92	1.02	1.04	1.08	0.99	0.0186	0.5850	0.0109
21	Descent/RTB	0.64	0.92	0.69	0.89	0.94	0.95	0.82	0.0138	1.0413	0.0143
22	Circuits	-	0.90	0.72	0.99	0.98	-	0.92	0.0098	0.7963	0.0078
23	Land	0.77	1.02	0.71	0.95	1.03	0.94	0.91	0.0148	0.8431	0.0124
24	Taxy (post-flight)	0.53	1.07	0.82	0.91	0.96	1.27	0.97	0.0114	1.0322	0.0117

Table A4.5 Mean values for tidal volume - all sorties combined
[L(BTPS).min⁻¹]

	Phase	GN1 (RAE)	GN1 (TWU)	SCM (RAE)	SCM (TWU)	GN2 (TWU)	ACM (TWU)	Grand Mean	Sigma Squared Within Phase	Error Ratio	Sigma Squared Between Subject
1	Strap-in	-	1.08	-	1.05	1.01	1.15	1.07	0.0391	0.6223	0.0243
2	Taxy (pre-flight)	-	1.00	-	1.01	1.05	1.08	1.02	0.0296	0.4187	0.0124
3	Take-off	-	1.09	-	1.13	1.15	1.35	1.14	0.0158	1.2774	0.0202
4	Climb	-	1.03	-	0.94	0.92	1.03	0.96	0.0190	0.5447	0.0103
5	Cruise	-	0.96	-	0.99	0.92	0.96	0.95	0.0135	1.0016	0.0135
6	2G Turns	-	0.91	-	-	-	-	0.91	0.0090	1.1498	0.0103
7	3G Turns	-	0.91	-	-	-	-	0.91	0.0138	0.8050	0.0111
8	4G Turns	-	0.89	-	-	-	-	0.89	0.0077	6.8706	0.0531
9	Loops	-	1.03	-	1.01	-	-	1.02	0.0087	3.7722	0.0327
10	Rolls	-	1.02	-	-	-	-	1.02	0.0087	4.3284	0.0376
11	Aerobatics	-	0.98	-	-	0.94	-	0.95	0.0128	2.3071	0.0296
12	High G Spirals	-	-	-	0.83	-	-	0.83	0.0246	0.0000	0.0000
13	6G Spirals	-	-	-	0.86	-	-	0.86	0.0261	0.6609	0.0172
14	Level Turns	-	0.94	-	0.93	0.83	-	0.90	0.0033	2.7031	0.0088
15	Barrel Rolls	-	-	-	1.09	-	-	1.09	0.0006	31.4459	0.0204
16	Low Level	-	-	-	-	0.93	-	0.93	0.0130	1.3570	0.0177
17	Steep Turns	-	-	-	-	0.88	-	0.88	0.0064	2.3894	0.0153
18	Wind-up Turns	-	-	-	-	0.80	-	0.80	0.0136	0.0000	0.0000
19	ACM	-	-	-	-	-	1.23	1.23	0.0168	0.0000	0.0000
20	Recovery	-	1.05	-	1.08	1.06	1.09	1.06	0.0150	1.5925	0.0240
21	Descent/RTB	-	0.92	-	0.90	1.01	0.97	0.93	0.0116	0.9945	0.0116
22	Circuits	-	0.87	-	0.96	0.99	-	0.91	0.0111	0.9335	0.0104
23	Land	-	0.98	-	0.98	0.99	0.94	0.98	0.0051	4.3327	0.0223
24	Taxy (post-flight)	-	1.10	-	0.97	0.97	1.31	1.05	0.0115	1.4669	0.0168

Table A4.6 Mean values for tidal volume - PCO_2 sorties
[L(BTPS).min⁻¹]

	Phase	GW1 (RAE)	GW1 (TWU)	SCM (RAE)	SCM (TWU)	GW2 (TWU)	ACM (TWU)	Grand Mean	Sigma Squared Within Phase	Error Ratio	Sigma Squared Between Subject
1	Strap-in	-	12.62	-	11.12	11.22	12.09	11.99	5.6804	0.3604	2.0472
2	Taxy (pre-flight)	10.19	12.47	6.94	12.31	12.25	12.25	12.05	4.0193	0.2978	1.1969
3	Take-off	8.38	14.37	8.48	12.72	13.70	16.19	12.22	5.1494	1.1956	6.1566
4	Climb	9.02	13.40	5.89	10.11	10.72	12.38	9.30	6.3048	0.4599	2.8996
5	Cruise	6.01	11.45	7.05	10.82	11.20	13.27	9.42	3.9642	0.9649	3.8250
6	2G Turns	7.33	11.27	-	-	-	-	9.92	3.9401	1.0381	4.0902
7	3G Turns	8.74	12.27	-	-	-	-	11.11	4.8191	1.4210	6.8479
8	4G Turns	10.67	13.41	-	-	-	-	12.34	4.2681	2.9619	12.6417
9	Loops	13.36	16.00	15.13	14.85	-	-	15.06	3.6904	2.1892	8.0790
10	Rolls	11.57	16.06	-	-	-	-	14.34	4.2663	3.5108	14.9781
11	Aerobatics	11.39	15.89	-	12.82	14.99	-	14.46	7.7925	1.0048	7.8299
12	High G Spirals	-	-	11.75	13.00	-	-	12.29	27.8751	0.0000	0.0000
13	6G Spirals	-	20.80	16.19	14.60	-	-	15.26	27.7149	0.2156	5.9753
14	Level Turns	-	14.64	12.92	15.20	9.95	-	13.34	2.8556	2.8342	8.0935
15	Barrel Rolls	-	-	14.17	17.31	-	-	15.95	3.2249	2.9874	9.6341
16	Low Level	-	-	-	-	11.12	-	11.12	7.3250	0.5706	4.1796
17	Steep Turns	-	-	-	-	9.84	-	9.84	1.8970	1.7337	3.2889
18	Wind-up Turns	-	-	-	-	13.21	-	13.21	16.2740	0.0000	0.0000
19	ACM	-	-	-	-	-	23.66	23.66	12.4833	[illegible]	3.2744
20	Recovery	9.73	13.95	13.42	15.57	14.36	17.58	13.59	10.4658	0.6897	7.2183
21	Descent/RIB	4.79	11.04	6.94	11.03	10.96	10.67	9.01	3.7741	1.0973	4.1414
22	Circuits	-	11.47	7.65	13.44	13.12	-	11.85	3.5514	1.8636	6.6184
23	Land	8.40	13.43	7.22	12.08	12.86	12.21	11.05	5.3160	0.6901	3.6686
24	Taxy (post-flight)	3.69	14.20	9.12	11.15	10.97	12.83	11.64	3.5807	0.5453	1.9526

Table A4.7 Mean values for alveolar ventilation - all sorties combined
[L(BTPS).min $^{-1}$]

	Phase	GW1 (RAE)	GW1 (TWU)	SCM (RAE)	SCM (TWU)	GW2 (TWU)	ACM (TWU)	Grand Mean	Sigma Squared Within Phase	Error Ratio	Sigma Squared Between Subject
1	Strap-in	-	12.62	-	12.14	11.72	12.35	12.40	6.6441	0.4471	2.9706
2	Taxy (pre-flight)		12.40	-	12.36	12.50	12.29	12.38	3.8799	0.2680	1.0398
3	Take-off	-	14.14	-	13.01	13.17	16.00	13.83	3.3212	0.4928	1.6367
4	Climb	-	12.59	-	9.79	10.29	12.36	10.54	5.7790	0.0559	0.3230
5	Cruise	-	11.09	-	11.10	10.88	13.29	11.11	2.7212	0.9647	2.6251
6	2G Turns	-	11.05	-	-	-	-	11.05	3.0722	1.1616	3.5687
7	3G Turns	-	11.69	-	-	-	-	11.69	4.1438	1.5304	6.3417
8	4G Turns	-	12.38	-	-	-	-	12.38	4.2175	2.1094	8.8963
9	Loops	-	15.23	-	14.26	-	-	14.64	4.7562	1.6388	7.7944
10	Rolls	-	14.97	-	-	-	-	14.97	3.8986	3.8765	15.1128
11	Aerobatics	-	15.40	-	-	13.63	-	14.12	7.5593	0.0000	[illegible]
12	High G Spirals	-	-	-	10.99	-	-	10.99	19.1016	0.0000	0.0000
13	6G Spirals	-	-	-	14.01	-	-	14.01	32.1510	0.0235	0.7555
14	Level Turns	-	14.25	-	14.63	9.55	-	12.91	2.4469	0.5199	1.2721
15	Barrel Rolls	-	-	-	18.86	-	-	18.86	1.4365	4.1288	[illegible]
16	Low Level	-	-	-	-	10.27	-	10.27	2.5223	0.3250	0.8197
17	Steep Turns	-	-	-	-	9.21	-	9.21	1.6782	0.0267	0.0448
18	Wind-up Turns	-	-	-	-	9.66	-	9.66	1.1552	0.0000	0.0000
19	ACM	-	-	-	-	-	23.66	23.66	12.4833	0.3773	4.7099
20	Recovery	-	13.43	-	16.70	15.25	17.96	14.86	6.6187	1.3384	8.8584
21	Descent/RIB	-	10.76	-	11.23	11.08	10.77	10.96	2.8137	0.5321	1.4972
22	Circuits	-	10.33	-	12.73	12.75	-	11.37	2.6845	1.3609	3.6534
23	Land	-	12.25	-	[illegible]	11.82	11.65	12.06	1.7851	0.9906	1.7683
24	Taxy (post-flight)	-	14.54	-	11.98	11.10	13.29	[illegible]	3.1359	0.2737	0.8583

Table A4.8 Mean values for alveolar ventilation - PCO_2 sorties
[L(BTPS).min $^{-1}$]

	Phase	GH1 (RAE)	GH1 (TWU)	SCM (RAE)	SCM (TWU)	GH2 (TWU)	ACM (TWU)	Grand Mean	Sigma Squared Within Phase	Error Ratio	Sigma Squared Between Subject
1	Strap-in	-	86.27	-	77.59	80.79	81.35	82.74	127.2370	3.2466	413.0876
2	Taxy (pre-flight)	86.33	81.24	80.04	73.72	81.84	79.45	7[illegible].86	128.2520	2.1761	279.0892
3	Take-off	93.06	86.35	76.72	73.83	80.74	91.75	82.[illegible]	147.8520	2.3720	350.7049
4	Climb	93.27	87.40	81.92	74.14	82.93	81.85	79.77	186.1310	1.5422	287.0512
5	Cruise	84.13	79.68	87.13	86.53	84.93	103.60	84.41	233.3390	1.2441	290.2970
6	2G Turns	79.75	76.99	-	-	-	-	77.94	160.6260	2.1731	349.0564
7	3G Turns	79.61	82.34	-	-	-	-	81.45	180.7690	1.7063	308.4461
8	4G Turns	86.70	91.62	-	-	-	-	89.71	236.9460	2.4992	592.1754
9	Loops	101.45	102.60	112.29	95.78	-	-	101.72	83.9229	4.4787	375.8655
10	Rolls	95.47	106.40	-	-	-	-	102.23	140.8380	4.4113	621.2787
11	Aerobatics	127.29	86.96	-	77.96	100.82	-	94.15	269.6800	1.3577	366.1445
12	High G Spirals	-	-	92.98	103.29	-	-	97.45	251.7820	1.9621	494.0215
13	6G Spirals	-	113.07	112.23	95.89	-	-	101.36	256.1550	0.6564	168.1401
14	Level Turns	-	148.88	101.17	98.48	72.70	-	95.53	56.0278	7.6087	426.2987
15	Barrel Rolls	-	-	108.03	110.90	-	-	109.65	13.9611	25.8279	360.5859
16	Low Level	-	-	-	-	91.49	-	91.49	290.8890	0.5762	167.6102
17	Steep Turns	-	-	-	-	75.10	-	75.10	111.8310	3.7435	418.6393
18	Wind-up Turns	-	-	-	-	91.83	-	91.83	95.6403	7.3018	698.3463
19	ACM	-	-	-	-	-	144.91	144.91	254.5680	2.8183	717.4490
20	Recovery	92.67	94.20	105.83	101.07	99.67	123.72	98.47	242.1150	1.8736	453.6267
21	Descent/RTB	78.57	90.60	79.20	80.59	85.21	86.77	82.96	159.1920	1.3496	214.8455
22	Circuits	-	94.23	89.03	92.79	82.40	-	90.66	143.2670	2.0268	290.3736
23	Land	79.34	99.56	73.83	85.67	93.23	102.50	87.45	232.4300	0.6476	150.5217
24	Taxy (post-flight)	52.02	101.84	78.39	88.57	86.55	103.97	90.94	130.3570	1.1996	156.3763

Table A4.9 Mean values for peak inspiratory flow - all sorties combined
[L(BTPS).min^{-1}]

	Phase	GH1 (RAE)	GH1 (TWU)	SCM (RAE)	SCM (TWU)	GH2 (TWU)	ACM (TWU)	Grand Mean	Sigma Squared Within Phase	Error Ratio	Sigma Squared Between Subject
1	Strap-in		90.79	-	91.45	101.32	87.36	91.54	120.9070	3.8145	[illegible]61.1998
2	Taxy (pre-flight)	-	85.87	-	77.04	90.81	80.43	83.22	139.3840	1.5926	221.9830
3	Take-off	-	89.57	-	82.65	97.71	98.82	89.64	60.6576	9.0028	546.0882
4	Climb	-	91.61	-	75.48	90.39	81.54	80.49	140.2520	2.1089	295.7774
5	Cruise	-	79.25	-	89.63	89.58	107.20	85.64	187.4820	1.8214	[illegible]41.4797
6	2G Turns	-	77.20	-	-	-	-	77.20	73.3982	6.4927	476.5525
7	3G Turns	-	81.10	-	-	-	-	81.10	197.5680	2.0407	403.1770
8	4G Turns	-	90.85	-	-	-	-	90.85	219.1330	4.7625	1043.6209
9	Loops	-	99.77	-	90.23	-	-	93.87	102.1230	2.9147	297.6579
10	Rolls	-	103.36	-	-	-	-	103.36	117.9770	10.3267	1218.3131
11	Aerobatics	-	86.41	-	-	100.58	-	96.64	169.2150	4.3878	742.4816
12	High G Spirals	-	-	-	94.81	-	-	94.81	368.1880	0.6506	239.5431
13	6G Spirals	-	-	-	92.67	-	-	92.67	302.1620	0.3427	103.5509
14	Level Turns	-	158.46	-	94.10	76.44	-	92.50	46.7928	9.8305	459.9966
15	Barrel Rolls	-	-	-	113.24	-	-	113.24	0.3120	0.0000	0.0000
16	Low Level	-	-	-	-	91.10	-	91.10	236.0650	1.6357	386.1315
17	Steep Turns	-	-	-	-	77.27	-	77.27	87.1607	11.0137	959.9618
18	Wind-up Turns	-	-	-	-	67.18	-	67.18	49.0050	0.0000	0.0000
19	ACM	-	-	-	-	-	144.91	144.91	254.5680	3.8428	978.2539
20	Recovery	-	93.20	-	106.70	101.31	127.53	100.44	244.1890	1.9524	476.7546
21	Descent/RTB	-	91.09	-	89.43	89.67	93.96	90.82	127.9560	2.4290	310.8051
22	Circuits	-	93.35	-	97.06	84.46	-	93.00	115.1680	2.4173	278.3956
23	Land	-	99.85	-	86.1[illegible]	103.87	109.53	96.18	62.4584	6.5221	407.3599
24	Taxy (post-flight)	-	98.81	-	87.56	82.62	104.32	91.81	119.7920	2.2435	268.7534

Table A4.10 Mean values for peak inspiratory flow - PCO$_2$ sorties
[L(BTPS).min^{-1}]

	Phase	GW1 (RAE)	GW1 (TWU)	SCM (RAE)	SCM (TWU)	GW2 (TWU)	ACM (TWU)	Grand Mean	Sigma Squared Within Phase	Error Ratio	Sigma Squared Between Subject
1	Strap-in	-	43.76	-	42.01	41.66	37.31	42.53	4.4864	3.0093	13.5009
2	Taxy (pre-flight)	-	41.64	-	41.11	41.13	[illegible]	40.71	1.2942	11.7592	15.2185
3	Take-off	-	42.66	-	43.31	43.12	41.18	42.78	4.0809	1.9037	7.7689
4	Climb	-	40.38	-	36.51	37.85	38.22	37.51	8.6155	0.3337	2.8750
5	Cruise	-	36.82	-	34.92	36.30	35.70	36.20	5.6484	0.9888	5.5852
6	2G Turns	-	35.83	-	-	-	-	35.83	4.3696	5.5892	24.4225
7	3G Turns	-	35.55	-	-	-	-	35.55	4.9516	4.0845	20.2250
8	4G Turns	-	34.37	-	-	-	-	34.37	5.7714	3.0969	17.8735
9	Loops	-	35.21	-	34.13	-	-	34.54	0.9092	15.0317	13.6673
10	Rolls	-	36.66	-	-	-	-	36.68	5.8357	2.0121	11.7421
11	Aerobatics	-	36.65	-	-	34.61	-	35.18	1.5591	6.7900	10.5866
12	High G Spirals	-	-	-	33.39	-	-	33.39	1.2360	3.9946	4.9374
13	6G Spirals	-	-	-	33.80	-	-	33.80	3.5489	1.2743	4.5224
14	Level Turns	-	26.07	-	34.51	33.32	-	33.55	0.9776	[illegible]	5.2922
15	Barrel Rolls	-	-	-	35.31	-	-	35.31	8.8200	[illegible]	1.3724
16	Low Level	-	-	-	-	40.05	-	40.05	1.9709	5.0300	9.9138
17	Steep Turns	-	-	-	-	35.33	-	35.33	1.8154	5.2161	9.4695
18	Wind-up Turns	-	-	-	-	30.21	-	30.21	0.0220	0.0000	0.0000
19	ACM	-	-	-	-	-	35.58	35.58	3.9456	0.8474	3.3435
20	Recovery	-	36.35	-	35.78	33.33	35.97	36.02	3.5938	4.0588	14.5864
21	Descent/RTB	-	37.97	-	36.94	37.01	37.31	37.41	3.0851	4.5791	14.1271
22	Circuits	-	37.98	-	40.46	37.57	-	38.60	1.8898	1.2136	2.2935
23	Land	-	39.06	-	38.17	37.37	39.09	38.48	6.4862	2.3246	15.0779
24	Taxy (post-flight)	-	36.98	-	36.23	35.75	37.47	36.51	1.9432	6.6924	13.0047

Table A4.11 Mean values for carbon dioxide tensions
[mmHg]

	Phase	GW1 (RAE)	GW1 (TWU)	SCM (RAE)	SCM (TWU)	GW2 (TWU)	ACM (TWU)	Grand Mean	Sigma Squared Within Phase	Error Ratio	Sigma Squared Between Subject
1	Strap-in	-	0.63	-	0.59	0.56	0.55	0.61	0.0205	0.1270	0.0026
2	Taxy (pre-flight)	-	0.59	-	0.60	0.60	0.57	0.59	0.0095	0.2338	0.0022
3	Take-off	-	0.69	-	0.65	0.63	0.79	0.68	0.0114	0.0000	0.0000
4	Climb	-	0.60	-	0.42	0.45	0.55	0.46	0.0188	0.0000	0.0000
5	Cruise	-	0.47	-	0.44	0.46	0.54	0.46	0.0066	0.5241	0.0035
6	2G Turns	-	0.45	-	-	-	-	0.45	0.0069	0.3822	0.0026
7	3G Turns	-	0.48	-	-	-	-	0.48	0.0083	0.5137	0.0042
8	4G Turns	-	0.48	-	-	-	-	0.48	0.0080	0.8388	0.0067
9	Loops	-	0.61	-	0.57	-	-	0.58	0.0073	0.5503	0.0040
10	Rolls	-	0.63	-	-	-	-	0.63	0.0072	4.3845	0.0316
11	Aerobatics	-	0.67	-	-	0.54	-	0.58	0.0126	0.2793	0.0035
12	High G Spirals	-	-	-	0.42	-	-	0.42	0.0242	0.0000	0 0000
13	6G Spirals	-	-	-	0.54	-	-	0.54	0.0383	0.1296	0.0050
14	Level Turns	-	0.43	-	0.59	0.37	-	0.51	0.0039	1.5117	0.0059
15	Barrel Rolls	-	-	-	0.77	-	-	0.77	0.0001	31.0656	0.0128
16	Low Level	-	-	-	-	0.48	-	0.48	0.0064	0.1294	0.0008
17	Steep Turns	-	-	-	-	0.37	-	0.37	0.0031	0.0000	0.0000
18	Wind-up Turns	-	-	-	-	0.34	-	0.34	0.0013	0.0000	0.0000
19	ACM	-	-	-	-	-	0.96	0.96	0.0193	2.1777	0.0421
20	Recovery	-	0.57	-	0.69	0.60	0.77	0.62	0.0117	1.5011	0.0175
21	Descent/RTB	-	0.47	-	0.48	0.48	0.46	0.47	0.0045	0.7533	0.0034
22	Circuits	-	0.45	-	0.59	0.55	-	0.51	0.0059	0.9744	0.0058
23	Land	-	0.55	-	0.54	0.49	0.52	0.53	0.0065	0.0618	0.0004
24	Taxy (post-flight)	-	0.60	-	0.52	0.48	0.49	0.54	0.0052	0.0428	0.0002

Table A4.12 Mean values for carbon dioxide production
[L(STPD).min^{-1}]

	Phase	GH1 (RAE)	GH1 (TWU)	SCM (RAE)	SCM (TWU)	GR2 (TWU)	ACM (TWU)	Grand Mean	Sigma Squared Within Phase	Error Ratio	Sigma Squared Between Subject
1	Strap-in	-	101.62	-	92.04	87.88	85.85	96.55	0.5172	0.0997	0.0516
2	Taxy (pre-flight)	-	94.33	-	94.80	96.40	87.87	93.73	0.2339	0.2562	0.0599
3	Take-off	-	110.00	-	101.83	101.33	125.50	107.68	0.2848	0.0000	0.0000
4	Climb	-	94.37	-	65.47	71.67	86.20	73.01	0.4574	0.0000	0.0000
5	Cruise	-	74.62	-	68.62	71.70	84.40	72.61	0.1651	0.3988	0.0658
6	2G Turns	-	72.15	-	-	-	-	72.15	0.1735	0.4210	0.0730
7	3G Turns	-	76.22	-	-	-	-	76.22	0.2177	0.6748	0.1469
8	4G Turns	-	77.20	-	-	-	-	77.20	0.2004	0.6297	0.1262
9	Loops	-	98.36	-	88.56	-	-	92.30	0.1663	0.6499	0.1081
10	Rolls	-	100.74	-	-	-	-	100.74	0.1893	3.7754	0.7147
11	Aerobatics	-	105.17	-	-	87.84	-	92.65	0.3348	0.8804	0.2947
12	High G Spirals	-	-	-	65.11	-	-	65.11	0.5728	0.0000	0.0000
13	6G Spirals	-	-	-	85.63	-	-	85.63	1.0051	0.1014	0.1019
14	Level Turns	-	70.00	-	97.14	60.66	-	80.17	0.0918	0.9867	0.0906
15	Barrel Rolls	-	-	-	121.75	-	-	121.75	0.0045	18.9910	0.5355
16	Low Level	-	-	-	-	76.49	-	76.49	0.1719	0.0000	0.0000
17	Steep Turns	-	-	-	-	59.85	-	59.85	0.0834	0.0796	0.0066
18	Wind-up Turns	-	-	-	-	50.50	-	50.50	0.0245	0.0000	0.0000
19	ACM	-	-	-	-	-	151.33	151.33	0.4969	1.5302	0.7603
20	Recovery	-	90.10	-	108.32	95.12	120.52	97.85	0.2942	1.3670	0.4021
21	Descent/RTB	-	74.52	-	76.09	76.46	71.57	74.84	0.1160	0.5477	0.0635
22	Circuits	-	73.71	-	95.39	88.55	-	81.99	0.1621	0.6209	0.1007
23	Land	-	87.80	-	84.50	80.50	82.00	84.73	0.1603	0.0000	0.0000
24	Taxy (post-flight)	-	93.44	-	81.58	79.62	92.40	85.62	0.1362	0.0345	0.0047

Table A4.13 Mean values for energy expenditure
[kcal.m^{-2}.h^{-1}]

	Phase	Respiratory Freqeancy		Minute Velume		Tidai Veiuma		Aiveelar Ventiietion		Peak Iespiratory Flow	
		RAE	TWU	RAE	TWU	RAE	TWU	RAE	TWU	RAE	TWU
1	Strap-in		4 1 3 2		2 1 3 4		2 3 1 4		2 3 4 1		2 3 4 1
2	Taxy (pre-flight)	2 1	4 2 3 1	2 1	1 4 2 3	2 1	2 1 3 4	2 ≤ 1	4 3 2 1	2 1	2 4 1 3
3	Take-off	1 2	4 2 3 1	1 2	2 1 3 4	2 1	2 3 1 4	1 2	2 3 1 4	2 1	2 3 1 4
4	Climb	2 1	2 4 3 1	2 1	2 3 1 4	2 1	3 2 4 1	2 1	2 3 4 1	2 1	2 4 3 1
5	Cruise	1 2	2 1 3 4	1 2	1 2 3 4	1 2	3 2 1 4	1 2	2 3 1 4	1 2	1 3 2 4
6	2G Turns										
7	3G Turns										
8	4G Turns										
9	Loop	1 2	1 2	1 2	1 2	1 2	2 1	1 2	2 1	1 2	2 1
10	Rolls										
11	Aerobatics		2 1 3		2 3 1		2 3 1		2 3 1		[illegible] 1 3
12	High G Spirals										
13	6G Spirals		1 2		2 1		2 ≤ 1		2 1		2 1
14	Level Turns		3 1 2		3 1 2		3 1 2		3 1 2		3 2 ≤ 1
15	Barrel Rolls										
16	Low Level										
17	Steep Turns										
18	Wind-up Turns										
19	ACM										
20	Recovery	1 2	1 3 2 4	1 2	1 3 2 4	1 2	2 3 1 4	1 2	1 3 2 4	1 2	1 3 2 4
21	Descent/RTB	1 ≤ 2	4 1 3 2	1 2	1 4 2 3	1 2	2 1 3 4	1 2	4 3 2 1	1 2	2 3 4 1
22	Circuits		3 1 2		1 ≤ 3 2		1 ≤ 3 2		1 ≤ 3 2		3 2 1
23	Land	2 1	3 1 4 2	2 1	2 1 4 3	2 1	4 2 1 3	2 1	2 4 3 1	2 1	2 3 1 4
24	Taxy (post-flight)	2 1	4 3 1 2	1 2	3 2 4 1	1 ≤ 2	2 3 1 4	1 ≤ 2	3 2 4 1	1 2	3 2 1 4

Table A4.14 Phase comparisons with trial groups - all sorties combined
[Sortie profiles are here represented by numbers (1 = GH1, 2 = SCM, 3 = GH2, 4 = ACM) and are arranged in rank order. For explanation, see text pA5]

	Phase	Respiratory Frequency	Minute Volume	Tidal Volume	Alveolar Ventilation	Peak Inspiratory Flow	Carbon Dioxide Tension	Carbon Dioxide Production	Energy Expenditure
		TWU	TWU	TWU	TWU	TWU	TWU	TWU	TWU
1	Strap-in	4 2 1 3	1 2 3 4	3 2 1 4	3 2 4 1	4 1 2 3	4 ≤ 3 2 1	4 3 2 1	4 3 2 1
2	Taxy (pre-flight)	4 2 3 1	1 4 2 3	1 2 3 4	4 2 1 3	2 4 1 3	4 2 3 1	4 1 3 2	4 1 2 3
3	Take-off	4 2 3 1	2 1 3 4	1 2 3 4	2 3 1 4	2 1 3 4	4 1 3 2	3 2 1 4	3 2 1 4
4	Climb	2 1 4 3	2 3 1 4	3 2 4 1	2 3 4 1	2 4 3 1	2 3 4 1	2 3 4 1	2 3 4 1
5	Cruise	2 1 3 4	1 2 3 4	3 4 1 2	3 1 2 4	1 3 2 4	2 4 3 1	2 3 1 4	2 3 1 4
6	2G Turns								
7	3G Turns								
8	4G Turns								
9	Loops	1 2	1 2	2 1	2 1	2 1	2 1	2 1	2 1
10	Rolls								
11	Aerobatics	3 1	3 1	3 1	3 1	1 3	3 ≤ 1	3 1	3 1
12	High G Spirals								
13	6G Spirals								
14	Level Turns	3 1 2	3 2 1	3 2 1	3 1 2	3 2 ≤ 1	1 3 2	3 1 2	3 1 2
15	Barrel Rolls								
16	Low Level								
17	Steep Turns								
18	Wind-up Turns								
19	ACM								
20	Recovery	1 3 2 4	1 3 2 4	1 3 2 4	1 3 2 4	1 3 2 4	3 2 4 1	1 3 2 4	1 3 2 4
21	Descent/RTB	4 3 1 2	1 3 4 2	2 1 4 3	1 4 3 2	2 3 1 4	2 3 4 1	4 1 3 2	4 1 2 3
22	Circuits	3 1 2	1 3 2	1 2 3	1 ≤ 2 3	3 1 2	3 1 ≤ 2	1 ≤ 3 2	1 ≤ 3 2
23	Land	3 1 2 4	1 3 2 4	4 2 1 3	4 3 2 1	2 1 3 4	3 2 1 4	3 4 2 1	3 4 2 1
24	Taxy (post-flight)	4 3 1 2	3 2 1 4	3 2 1 4	3 2 4 1	3 2 1 4	3 2 1 4	3 2 4 1	3 2 4 1

Table A4.15 Phase comparisons - PCO_2 sorties
[Sortie profiles are here represented by numbers (1 = GH1, 2 = SCM, 3 = GH2, 4 = ACM) and are arranged in rank order. For explanation, see text pA5]

Sortie by Trial		Respiratory Frequency	Minute Volume
GH1	BAE	3,5,24,4,2,21,23,6,20,10,7,8,9,11	21,5,4,6,2,24,23,3,7,8,20,10,11,9
GH1	TWU	1,3,5,24,4,2,21,23,22,6,20,10,7,8,9,11,14,13	21,5,4,1,6,2,24,23,3,22,7,8,14,20,10,11,9,13
SCM	BAE	3,5,24,4,2,21,23,22,20,9,12,15,14,13	21,5,4,2,24,23,3,22,14,20,12,9,13,15
SCM	TWU	1,3,5,24,4,2,21,23,22,20,9,12,11,15,10,17	21,5,4,1,2,24,23,3,22,14,20,12,11,9,13,15
GH2	TWU	1,3,5,17,24,4,2,21,23,17,22,20 ≤ 10,11,14	17,21,5,4,1,2,16,24,23,3,22,10,14,20,11
ACM	TWU	1,3,5,24,4,2,23,24,21 ≤ 20	21,3,4,1,2,24,23,3,20 ≤ 19
		Tidal Volume	**Alveolar Ventilation**
GH1	BAE	6,21,7,5,8,4,23,11,24,2,20,10,9,3	21,5,6,4,24,23,7,2,3,8,20,11,10,9
GH1	TWU	6,21,7,5,14,8,4,23,22,11,10,2,13,1,20,10,9,3	21,5,6,4,1,24,23,7,2,22,3,8,14,20,11,10,9,13
SCM	BAE	21,5,14,4,12,23,22,24,2,13,20,9,3,15	21,5,4,24,23,2,22,3,12,14,20,9,13,15
SCM	TWU	21,5,14,12,4,22,23,11,24,2,13,1,20,9,3,15	21,5,4,1,24,23,2,22,3,12,14,20,11,9,13,15
GH2	TWU	17,21,10,5,16,14,4,22,23,11,24,2,1,20,3	21,17,5,4,1,16,24,23,2,22,3,10,14,20,11
ACM	TWU	21,5,4,23,24,2,1,20,3,19	21,5,4,1,24,23,2,3,20 ≤ 19
		Peak Inspiratory Flow	
GH1	BAE	4,5,2,[illegible],4,21,5,8,23,24,[illegible] 11	
GH1	TWU	[illegible],3,4,21,5,8,23,24,22,20,10,9,11,13	
SCM	BAE	[illegible],5,4,21,5,[illegible],2,14,20,12,9,13,15	
SCM	TWU	[illegible],5,23,24,22,14,20,12,[illegible],11,13,[illegible]	
GH2	TWU	17,[illegible],4,21,5,23,10,24,22,10,14,[illegible]	
ACM	TWU	2,1,3,4,21,5,21,24,20 ≤ 19	

Table A4.16 Sortie comparisons with trial groups - all sorties combined
[Phases of flight are here represented by numbers, as listed in Table A4.1 (pA6) and are arranged in rank order. For explanation, see text pA5]

Sortie by Trial	Respiratory Frequency	Minute Volume
GM1 TWO	1,3,4,24,5,2,21,23,6,22,20,7,10,9,8,14,11	5,21,4,6,1,7,23,2,22,24,3,8,14,20,9,10,11
SCM TWO	1,3,4,24,5,2,21,23,22,20,9,12,14,15,13	5,21,4,1,23,12,2,22,24,3,14,20,9,13 .S. 15
GM2 TWO	1,3,4,24,5,17,2,16,21,23,22,20,14,11,18	17,5,21,4,1,16,18,23,2,22,24,3,14,20,11
ACM TWO	1,3,4,24,5,2,21,23,20 .S. 19	5,21,4,1,23,2,24,3,20 .S. 19
	Tidal Volume	**Alveolar Ventilation**
GM1 TWO	8,7,14,6,21,23,22,4,11,9,10,2,1,24,20,3	21,5,6,4,7,23,1,22,8,2,24,14,3,9,20,10,11
SCM TWO	12,13,14,21,5,23,22,4,9,1,2,20,24,15,3	12,21,5,4,23,1,22,2,24,14,3,13,9,20 S 15
GM2 TWO	18,14,17,5,21,22,23,16,4,11,2,1,24,20,3	17,21,5,18,4,23,16,1,22,2,24,14,3,20,11
ACM TWO	21,5,23,4,1,2,20,24,19,3	21,5,4,23,1,2,24,3,20 .S. 19
	Peak Inspiratory Flow	**Carbon Dioxide Tension**
GM1 TWO	6,7,2,3,4,5,8,1,21,24,22,23,9,14,10,20,11	14,8,11,7,9,6,5,20,10,24,21,4,22,23 S 2,1,3
SCM TWO	2,3,4,5,1,21,24,22,23,9,14,20,12,13,15	12,13,14,15,9,5,20,24,21,4,22,23 S 2,1,3
GM2 TWO	18,2,17,3,4,5,1,21,24,22,23,14,16,20,11	18 .S. 14,11,17,5,20,24,21,4,22,23,16,2,1,3
ACM TWO	2,3,4,5,1,21,24,23,20 .S. 19	19,5,20,24,21,4,23 S 2,1,3
	Carbon Dioxide Production	**Energy Expenditure**
GM1 TWO	6,5,7,21,8,4,14,23,22,24,1,2,9,10,11,20,3	6,5,7,8,21,4,14,23,22,24,1,9,2,10,20,11,3
SCM TWO	12,5,21,4,14,23,22,24,13,9,1,2,20,3,15	12,5,21,4,14,23,22,24,13,1,9,2,20,3,15
GM2 TWO	18,17,5,21,4,14,23,16,22,24,1,2,20,11,3	18,17,5,21,4,14,23,22,16,24,1,2,20,11,3
ACM TWO	5,21,4,23,24,1,2,20,3 .S. 19	5,21,4,23,24,1,2,20,3 .S. 19

Table A4.17 Sortie comparisons - PCO_2 sorties
[Phases of flight are here represented by numbers, as listed in Table A4.1 (pA6) and are arranged in rank order. For explanation, see text pA5]

Phase	Term	Respiratory Frequency		Minute Volume		Tidal Volume		Alveolar Ventilation		Peak Inspiratory Flow		Carbon Dioxide Tension		Carbon Dioxide Production		Energy Expenditure	
		Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig
1	G	-	NS	-	NS	-	NS	-	NS	-	NS	-	*	-	NS	-	NS
2	G	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS
3	G	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS
4	G	-	NS	-	NS	-	NS	-	*	-	NS	-	*	0.000	***	0.000	***
5	G	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS
6	G	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
7	G	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
8	G	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
9	G	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS
10	G	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
11	G	0.619	NS	-	NS	0.601	NS	0.225	NS	0.116	NS	0.027	*	-	NS	-	NS
12	G	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS
13	G	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS
14	G	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS
15	G		NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS
16	G	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
17	G	-	NS		NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS
18	G	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS
19	G	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
20	G	-	*		**		NS	-	*	-	NS	-	NS	-	*		*
21	G	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS	-	NS
22	G	-	NS		*		*	0.000	***	-	NS	-	**	-	**		*
23	G	-	NS		NS		NS		NS	-	NS	-	NS	-	NS	-	NS
24	G		*	-	NS	-		-	NS	-	NS	-	NS	-	NS	-	NS

[For explanation, see text pA5] [NS = not significant]

Table A4.18 Phase by phase analysis of variance - PCO_2 sorties

Phase	Term	Respiratory Frequency		Minute Volume		Tidal Volume		Alveolar Ventilation		Peak Inspiratory Flow	
		Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig
1	G	-	NS	-	NS	-	NS	-	NS	0.583	NS
	T	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
	GT	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
2	G	0.569	NS	0.561	NS	0.650	NS	0.012	NS	0.155	NS
	T	0.765	NS	0.424	NS	0.022	*	0.000	***	0.573	NS
	GT	0.973	NS	0.508	NS	0.210	NS	0.091	NS	0.919	NS
3	G	0.726	NS	0.329	NS	0.255	NS	0.362	NS	0.026	*
	T	0.919	NS	0.231	NS	0.012	*	0.004	**	0.650	NS
	GT	0.229	NS	0.304	NS	0.779	NS	0.311	NS	0.679	NS
4	G	0.383	NS	0.041	*	0.003	**	0.004	**	0.047	*
	T	0.681	NS	0.272	NS	0.001	**	0.001	***	0.450	NS
	GT	0.052	NS	0.868	NS	0.623	NS	0.924	NS	0.821	NS
5	G	0.777	NS	0.431	NS	0.952	NS	0.738	NS	0.400	NS
	T	0.856	NS	0.170	NS	0.001	**	0.041	**	0.705	NS
	GT	0.319	NS	0.509	NS	0.607	NS	0.287	NS	0.730	NS
6	G	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
	T	0.801	NS	0.414	NS	0.014	*	0.003	**	0.787	NS
	GT	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
7	G	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
	T	0.993	NS	0.461	NS	0.075	NS	0.027	*	0.783	NS
	GT	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
8	G	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
	T	0.429	NS	0.700	NS	0.416	NS	0.169	NS	0.711	NS
	GT	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
9	G	0.392	NS	0.774	NS	0.555	NS	0.051	NS	0.817	NS
	T	0.672	NS	0.879	NS	0.977	NS	0.641	NS	0.408	NS
	GT	0.367	NS	0.745	NS	0.652	NS	0.387	NS	0.272	NS
10	G	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
	T	0.573	NS	0.311	NS	0.050	NS	0.043	*	0.418	NS
	GT	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
11	G	-	NS	-	NS	-	NS	-	NS	-	NS
	T	-	NS	-	NS	-	NS	-	NS	-	NS
	GT	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
12	G	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
	T	-	NS	-	NS	0.976	NS	0.510	NS	-	NS
	GT	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
13	G	0.143	NS	0.549	NS	0.014	*	0.288	NS	0.349	NS
	T	0.522	NS	0.306	NS	0.763	NS	0.496	NS	0.108	NS
	GT	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
14	G	-	NS	-	*	-	NS	-	**	-	**
	T	-	NS	-	NS	-	NS	-	NS		NS
	GT	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
15	G	-	NS	-	NS	-	NS	-	NS	-	NS
	T	-	NS	-	NS	-	NS	-	NS	-	NS
	GT	-	NS	-	NS	-	NS	-	NS	-	NS
16	G	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
	T	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
	GT	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
17	G	-	NS	-	NS	-	NS	-	NS	-	NS
	T	-	NS	-	NS	-	NS	-	NS	-	NS
	GT	-	NS	-	NS	-	NS	-	NS	-	NS
18	G	-	NS	-	NS	-	NS	-	NS	-	NS
	T	-	NS	-	NS	-	NS	-	NS	-	NS
	GT	-	NS	-	NS	-	NS	-	NS	-	NS
19	G	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
	T	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
	GT	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
20	G	0.000	***	0.027	*	0.975	NS	0.106	NS	0.120	NS
	T	0.764	NS	0.471	NS	0.029	*	0.067	NS	0.099	NS
	GT	0.295	NS	0.954	NS	0.269	NS	0.401	NS	0.584	NS
21	G	0.013	*	0.159	NS	0.900	NS	0.654	NS	0.810	NS
	T	0.737	NS	0.076	NS	0.002	**	0.000	***	0.450	NS
	GT	0.209	NS	0.344	NS	0.245	NS	0.123	NS	0.424	NS
22	G	-	NS	0.000	***	-	*	-	*	-	NS
	T	-	NS	0.141	NS	-	**	-	*	-	NS
	GT	1.000	NS	1.000	NS	1.000	NS	1.000	NS	1.000	NS
23	G	0.827	NS	0.706	NS	0.461	NS	0.538	NS	0.282	NS
	T	0.958	NS	0.008	**	0.003	**	0.001	**	0.077	NS
	GT	0.140	NS	0.404	NS	0.009	NS	[illegible]	NS	0.472	NS
24	G	0.008	**	-	NS	-	*	-	*	-	NS
	T	0.695	NS	-	NS	-	NS	-	*	-	NS
	GT	0.796	NS	-	NS	-	**	-	**	-	NS

Table A4.19 Phase by phase analysis of variance - all sorties combined
[for explenation of Term, see taxt pA5]
[for explanation of results, see text pA5]
(NS = not significant)

Phases	Term	Respiratory Frequency		Minute Volume		Tidal Volume		Alveolar Ventilation		Peak Inspiratory Flow		Carbon Dioxide Tension		Carbon Dioxide Production		Energy Expenditure	
		Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig
a. All	G	0.380	NS	0.278	NS	0.268	NS	0.803	NS	0.589	NS						
	T	0.742	NS	0.112	NS	0.002	**	0.000	***	0.739	NS						
	P	0.000	***	0.000	***	0.000	***	0.000	***	0.000	***						
	GT	0.919	NS	0.930	NS	0.397	NS	0.268	NS	0.881	NS						
	GP	0.064	NS	0.089	NS	0.078	NS	0.079	NS	0.099	NS						
b. PCO_2	G	-	NS	-	NS	0.027	*	-	NS	-	NS	0.245	NS	-	NS	-	NS
	P	-	***	-	***	-	***	-	**	-	**	-	***	-	**	-	**
	GP	-	NS	-	NS	0.038	*	-	NS	-	NS	-	NS	-	NS	-	NS

[For explanation of Term, see text pA5; for explanation of results, see text ; (NS = not significant)]

Table A4.20 All phases analysis of variance
a. all sorties combined b. PCO_2 sorties

Sorties	Source of Variation	Respiratory Frequency		Minute Volume		Tidal Volume		Alveolar Ventilation		Peak Inspiratory Flow		Carbon Dioxide Tension		Carbon Dioxide Production		Energy Expenditure	
		Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig	Prob	Sig
All	[a] Rou vs Man	0.0000	***	0.0000	***	0.0168	*	0.0000	***	0.0000	***						
	[a] Sortie type (G)	0.7675	NS	0.1253	NS	0.1825	NS	0.2309	NS	0.3653	NS						
	Trial type (T)	0.7334	NS	0.1121	NS	0.0030	**	0.0005	***	0.7362	NS						
	Sortie By Trial(GT)	0.9659	NS	0.8324	NS	0.5510	NS	0.3368	NS	0.7698	NS						
	Trial by Rou/Man	0.3445	NS	0.3424	NS	0.0053	**	0.1216	NS	0.7700	NS						
	[a] Sortie by Rou/Man	0.0000	***	0.0000	***	0.2573	NS	0.0001	***	0.0003	***						
PCO_2	Rou vs Man	-	***	-	***	0.3326	NS	-	**	-	**	0.0000	***	-	NS	-	NS
	Sortie type (G)	-		-	-	-	NS		-	-	-	-	-	-			
	Sortie by Rou/Man	-	*	-	*	0.1703	NS	-	-	-	*	0.2889	NS	-	-	-	*

[[a] Rou = Routine, Man = Manoeuvring; [b] for explanation of terms, see text pA5 for explanation of results, see text pA5 (NS - not significant);]
[[a] indicates principal differential differences, ie RCM - SCM - GM1 & GM2]

Table A4.21 Routine phases vs manoeuvring phases analysis of variance

7.5 Appendix E - Details of Individual Flights

Sortie	Subject	Type	CO2 or MCP	Duration (min)	Breaths (n)
1st Phase (RAE)					
01	MB	GH1	MCP	50	1043
02	MB	SCM	MCP	47	1041
03	HM	SCM	MCP	48	1280
04	GW	SCM	MCP	38	752
05	RR	GH1	MCP	48	1019
06	JA	GH1	MCP	51	730
07	HM	GH1	MCP	40	929
08	AA	GH1	MCP	39	869
09	AA	SCM	MCP	39	896
10	RR	SCM	MCP	48	841
11	JA	SCM	MCP	36	691
12	GW	GH1	MCP	37	675
2nd Phase (TWU)					
13	PJ	GH1	CO2	52	1028
14	SW	GH1	CO2	52	910
15	KB	GH1	CO2	56	1066
16	DM	GH1	CO2	54	938
17	AS	GH1	CO2	56	1122
18	PS	GH1	CO2	58	1219
19	MA	GH1	CO2	57	1211
20	DH	GH1	MCP	51	1151
21	JF	GH1	CO2	55	893
22	LB	GH1	CO2	56	1200
23	DF	GH1	MCP	44	927
24	RB	GH1	MCP	46	1150
25	PJ	SCM	CO2	55	1130
26	DM	SCM	CO2	57	1023
27	AS	SCM	CO2	52	1082
28	PS	SCM	CO2	55	1290
29	MA	SCM	MCP	46	1000
30	DH	SCM	MCP	47	1182
31	JF	SCM	CO2	45	661
32	SW	SCM	MCP	52	1034
33	LB	SCM	MCP	43	954
34	KB	SCM	MCP	53	1038
35	DF	SCM	CO2	39	898
36	DM	GH2	CO2	57	1046
37	PS	GH2	CO2	57	1304
38	AS	GH2	MCP	56	1160
39	PJ	GH2	MCP	55	1084
40	SW	GH2	CO2	52	1096
41	MA	GH2	CO2	53	1276
42	LB	GH2	CO2	58	1273
43	KB	GH2	MCP	56	1207
44	JF	GH2	CO2	58	854
45	DF	ACM	CO2	50	1031
46	JF	ACM	CO2	50	937
Total				2304	47141

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14. Abstract

The respiratory responses of experienced military pilots were studied during flight in a high performance jet aircraft. Over 38 hours of physiological monitoring was carried out involving over 47,000 breaths.

The importance and relevance of information about these respiratory responses is reviewed, with particular emphasis on the difficulties of in-flight recording and the history of such experimentation in four specific areas of respiratory physiology: respiratory frequency and flow, added external resistance, hyperventilation and the metabolic cost of flying.

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